EINDHOVEN UNIVERSITY OF TECHNOLOGY

Department of Electrical Engineering

Identifying the flexibility potential of Dutch industrial parks using synthetic profiles

by

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MSC THESIS

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Summary

The Earth has had its resources aggressively exploited in the last decades. Alongside the depletion of its fossil-fuels reserves the planet has been experiencing a large amount of greenhouse gases (GHG) emissions into the atmosphere. These emissions are leading to a phenomenon denominated global warming. In order to mitigate the consequences of global warming (melting of ice glaciers that cause the levels of the ocean to rise, extreme weather events, etc.) measures against climate change need to be taken.

The Netherlands signed a national determined contribution with a target of reducing the country's dependence on fossil fuels. These ranged from a larger percentage of renewable energy in energy supply, through the electrification of heating, to widespread adoption of electric vehicles.

Renewable energy sources are, however, intrinsically intermittent. To make proper use of these new sources without massive changes in the current electricity system the use of flexibility is highly recommendable. Without the proper use of flexibility, there are risks of congestion in the electricity grid. The process of generating electricity from a source of renewable energy does not necessarily guarantee a cleaner energy mix. It also depends on when, where, and the flexibility sources available.

As the sector that has the highest energy consumption is the industry (commercial buildings included), the focus of this thesis is to assess the flexibility potential of industrial areas. The goal is to fulfil as much as possible of the industrial area with renewable electricity, while ensuring any surplus in production is used by flexibility, thus preventing the need for congestion management on a distribution network level. To this end, measured data from companies from the industrial park of Reiderland (Groningen, the Netherlands) were analysed. Two flexibility sources are chosen: electric vehicles and heat pumps. They were selected due to their importance in the electrification of energy system by replacing two major traditionally fossil-fuel powered streams: transport and heating.

This thesis answers the following main research question: *"In what way can a synthetic load profile, that can be applied to multiple types of businesses with minor changes, be used to assess the flexibility potential, given a certain amount of available RES?".* For this purpose, the companies are further divided into categories and normalised to make possible the creation of generic, wide-applicable synthetic profiles. Different aspects of the main research question are addressed through a set of sub-questions.

After the generic profiles for different types of industry are obtained, a fictitious industrial park is created through the selected profiles for each category. There is not enough data to develop a wide-applicable profile for the companies in the industry category (that probably depend on the kind of product they manufacture). Hence, with more data (not only from the industry category) the model can be greatly improved.

For the first comparison, a 400kW photovoltaic (PV) system (the only source of renewable energy used) is applied to the fictitious industrial park. Thus, the times when flexibility would be required to cope with the energy surplus of the system, how much energy surplus there is in a year, and an example of how to use this surplus are presented. Two different ways to visualise the PV surplus energy are displayed: the subtraction from the total electricity consumed by the fictitious industrial park, and as a ratio of PV energy generated over total electricity consumption. When the ratio is larger than one it means that there is an energy surplus in that period, when it is between zero and one it means that is only feeding the fictitious

park and indicates with what percentage of the energy is being fed by the solar system. The 400kW allows the production of over 25MWh of PV surplus energy, enough to charge the most popular fully electric vehicle in the Netherlands 441 times.

Finally, a sensitivity analysis, varying the size of the PV system, is conducted. It was found that by increasing the number of PV panels, the amount of surplus energy rises almost exponentially. With 80% the system is able to provide over 7 times the amount of surplus energy the original system provides, whereas with 20% less it generates around less than one third of the original system.

Nomenclature

AC	Alternating Current
B.V.	*Besloten Vennootschap* (Private Limited Company)
ASHP	Air source heat pump
BRP	Balance Responsible Party
CHP	Combined heat and power plant
COP	Coefficient of performance
DC	Direct Current
DSO	Distribution System Operator
EEA	European Economic Area
EU	European Union
EV	Electric Vehicle
FEV	Fully Electric Vehicle
GDPR	General Data Protection Regulation
GHG	Greenhouse Gas
GSHP	Ground source heat pump
HP	Heat Pump
HV	High voltage
HVDC	High Voltage Direct Current
ICE	Internal Combustion Engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISP	Imbalance Settlement Period
LV	Low voltage
MV	Medium voltage
NG	Natural Gas
NREL	National Renewable Energy Laboratory (United States)
PHEV	Plug-in Electric Vehicle
PTU	Program Time Unit
PV	Photovoltaic
RES	Renewable Energy Source
SQ	Sub-question
TSO	Transmission System Operator
UNFCCC	United Nations Framework Convention on Climate Change

Table of Contents

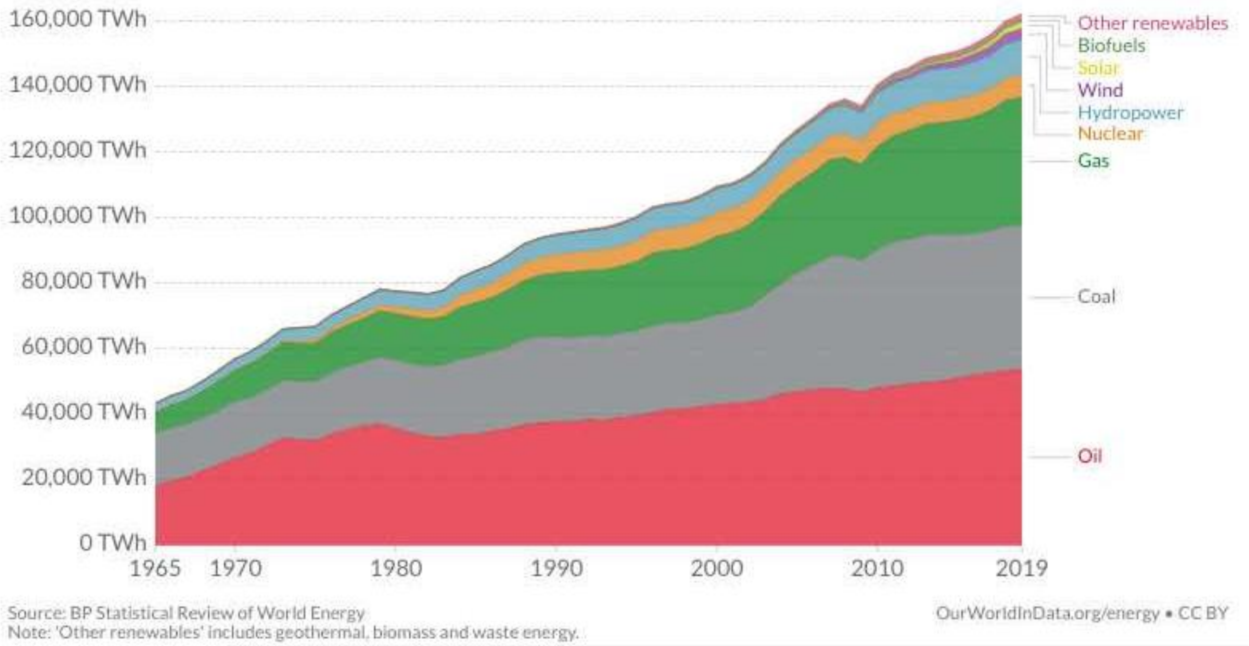
1 Introduction

In the last decades the world has undergone major changes. Standard of living, in general, has improved significantly. One of the reasons for this enhancement is the increased use of energy. Energy availability and reliability is directly related to the welfare of a country.

Energy has a two-way relationship with economic development: energy allows economic development by automated activities, and economic development allows more investments to be made in the production of energy [1].

Coal's use in some European countries (e.g., UK, France, Germany) and also in the USA and China took over 100 years to rise from marginal to the primary energy supply, which was previously dominated by traditional bio-fuels, such as wood [2]. In France and in the USA, coal became a significant source of energy in the late 1800s and in China during the 1960s [2].

After World War II hydrocarbons displaced wood and coal not only in Middle Eastern countries and in the USSR but also in Japan and in the Netherlands. Japan's share of crude oil as a primary energy source increased by 66% in 20 years [2]. In the Netherlands the discovery of the enormous Groningen Natural Gas (NG) field enabled the transition from coal to NG within one decade [3]. Figure 1 shows the evolution of the use of primary energy sources in the last century.



Source: BP Statistical Review of World Energy
Note: 'Other renewables' includes geothermal, biomass and waste energy.
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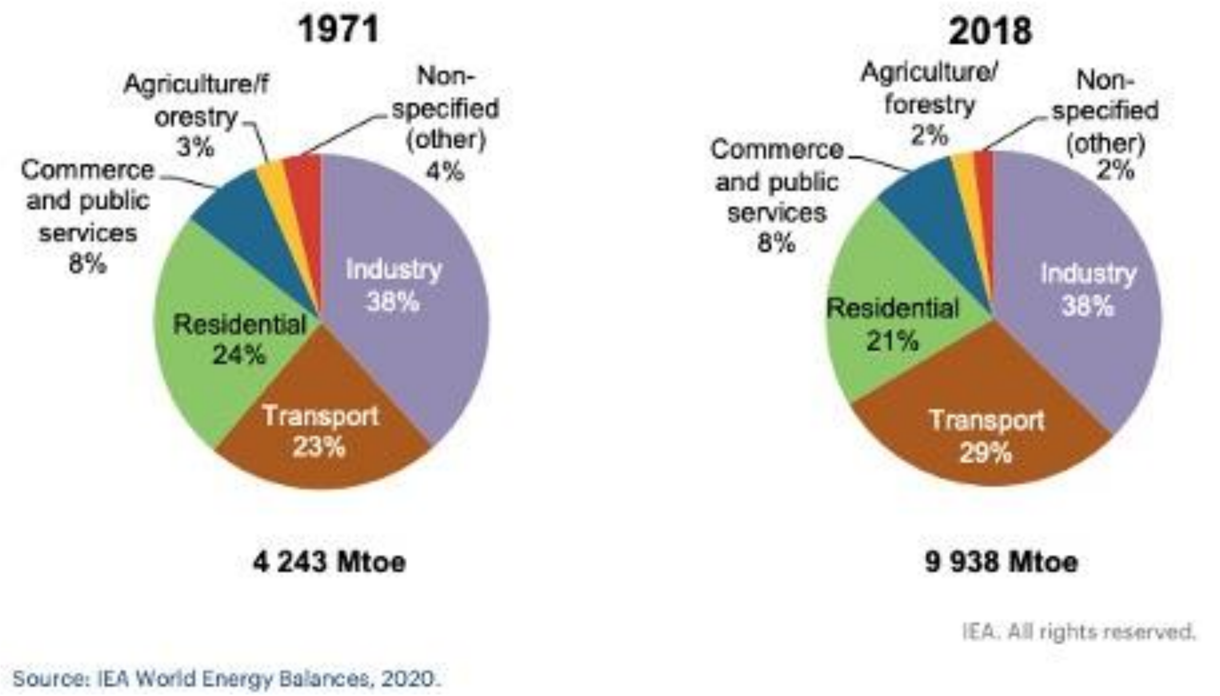
Figure 1: Energy consumption by source around the world [4]

The share of energy consumption of each sector has not changed much since 1971 [4]. It can be seen in Figure 2 that the sector whose consumption is the largest is the industry. The total energy consumption, however, has significantly increased.



Source: IEA World Energy Balances, 2020.

Figure 2: World total final consumption by sector [4]

In the Netherlands, the situation is similar as in the rest of the world. The industry is responsible for most of the total final energy consumption. If commercial and public services are added this number is even higher, as can be seen in Figure 3.

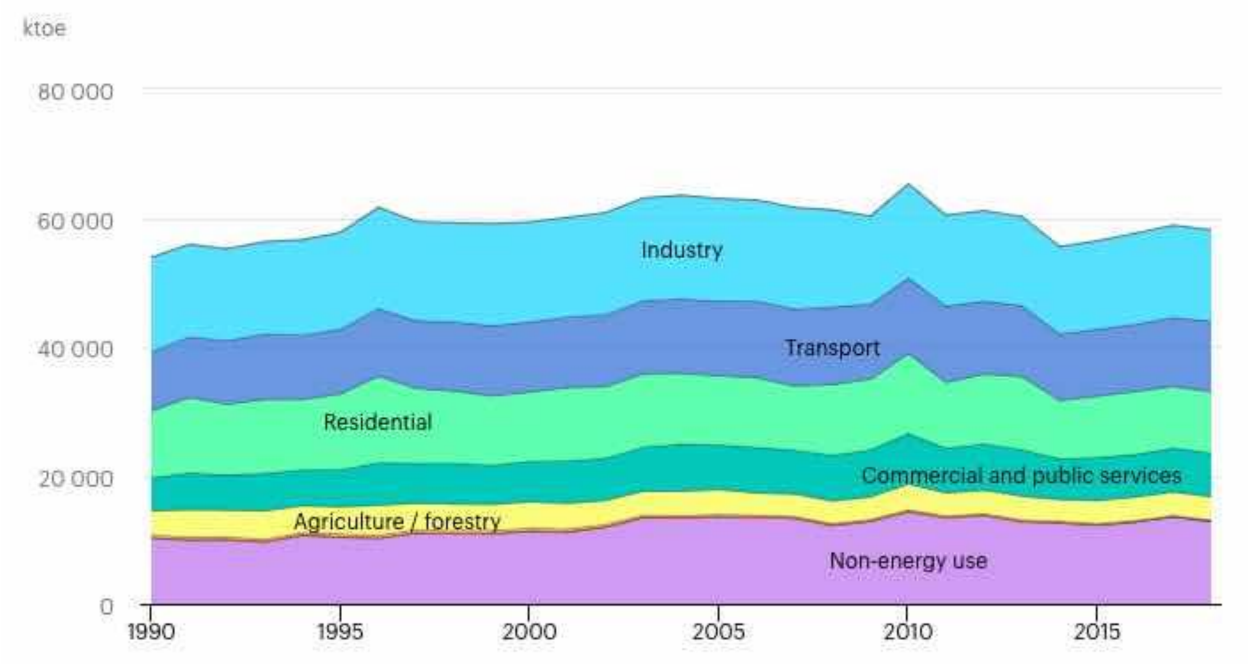


Figure 3: Total electricity consumption by sector in the Netherlands [3]

If energy continues to be produced and used in the traditional, centralised manner it will lead to the depletion of all fossil fuel reserves, that have taken years to be formed. Furthermore, it will accelerate the phenomenon known as Climate Change [5].

1.1 The Energy Transition

The increase in energy consumption in the last century has led to an unprecedented use of fossil fossils. Thus, the amount of greenhouse gas (GHG) emissions into the atmosphere has increased to record amounts, resulting in rising temperatures. This temperature increase may lead to severe consequences around the world, such as heat waves and the melting of ice glaciers.

The energy transition is a pathway towards transforming the global energy sector from the traditional fossil-fuel based to a less carbon intensive system by the second half of the 21st century. According to IRENA [6], renewable energy and energy efficiency can potentially reach 90% of the required reduction in carbon emissions.

A series of summits has been held among countries around the globe to mitigate global warming. In December 2015, at COP21 in Paris, the signatory parties of the United Nations Framework Convention on Climate Change (UNFCCC) came together to discuss policies and actions required to fight global warming. They reached an agreement that requires all parties to present a “nationally determined contribution”.

The focus of the Netherlands is shifting to a low-carbon energy system. However, the Netherlands has one of the highest GHG per capita in the EU. It surpasses the EU average and even Germany, as can be seen in Figure 4. This high average is due to the Netherlands’ dependence on fossil fuels [7]. A full explanation of how these emissions are calculated can be found in the statistical office of the European Union [8].

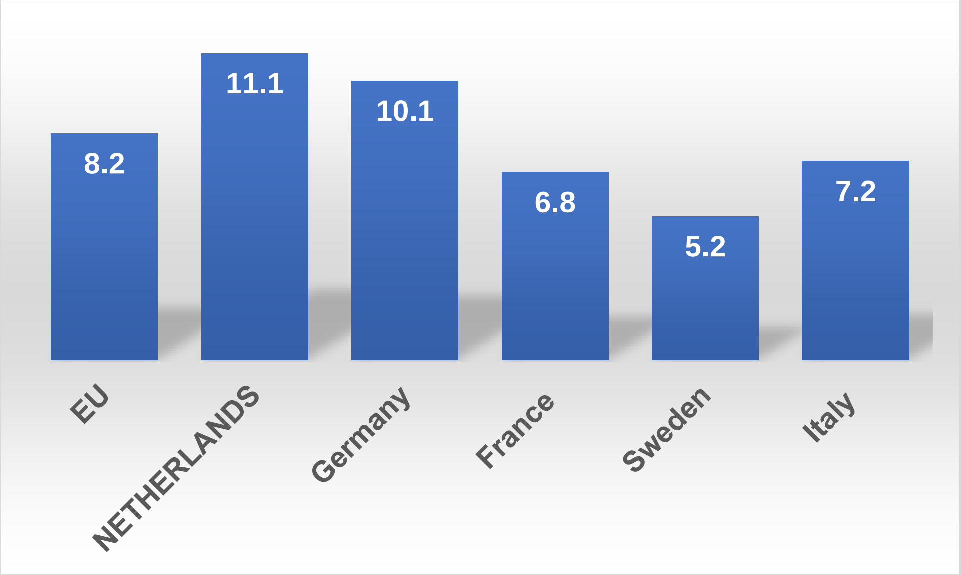


Figure 4: Average greenhouse gas emissions per person in tons of CO_2 equivalent in 2019 [8]

As an EU-member state, the Netherlands set the following legally binding targets (as per the 2019 Climate Act) for the years 2030 and 2050: reduction of greenhouse gas emissions by 49% and 95%, respectively, compared to 1990 levels, and for 100% of electricity to come from renewables by 2050 [3]. The rate of reduction is now not fast enough to achieve these goals [7]. Furthermore, the share of electricity in the total energy use is expected to grow with the increase in the number of electric vehicles and heat pumps [9].

In 2020 only 11.1% of the total energy consumption in the Netherlands came from renewable sources. This was a large increase compared to the 8.8% from 2019, mainly to the increased capacity for solar power and wind energy [10]. This increase can be seen in Figure 5.

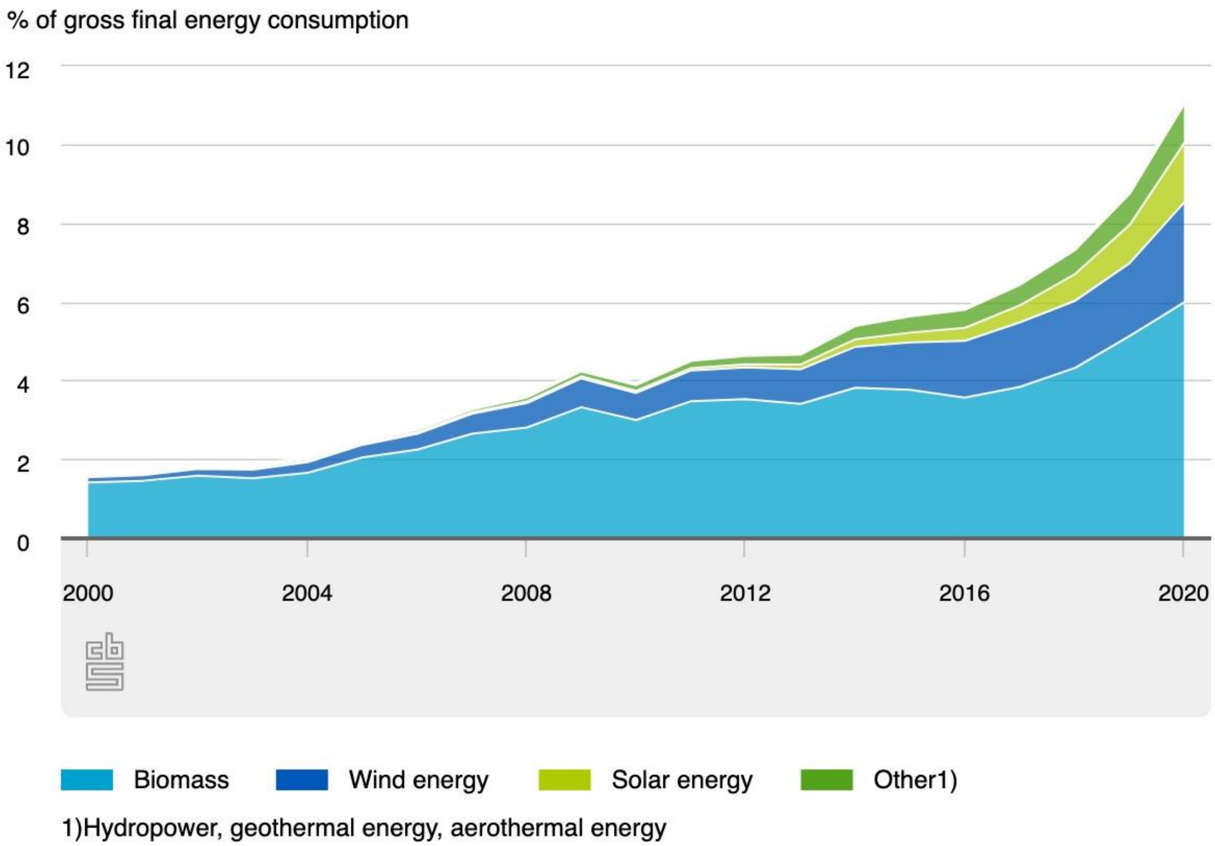


Figure 5: Share of renewable energy consumption in the Dutch energy matrix [10]

However, in the EU energy context it had been stipulated that this number should be at least 14% by 2020. Hence, the Netherlands signed a deal with Denmark to transfer the amount of renewable energy shortage [10].

From Figure 5, it can be seen that wind and solar energy had a significant increase in the last few years. For wind power this is mainly due to wind farm at Borssele [10]. For solar power, besides the addition of new solar parks, photo-voltaic (PV) panels had a substantial decrease in price. This is shown in Figure 6.

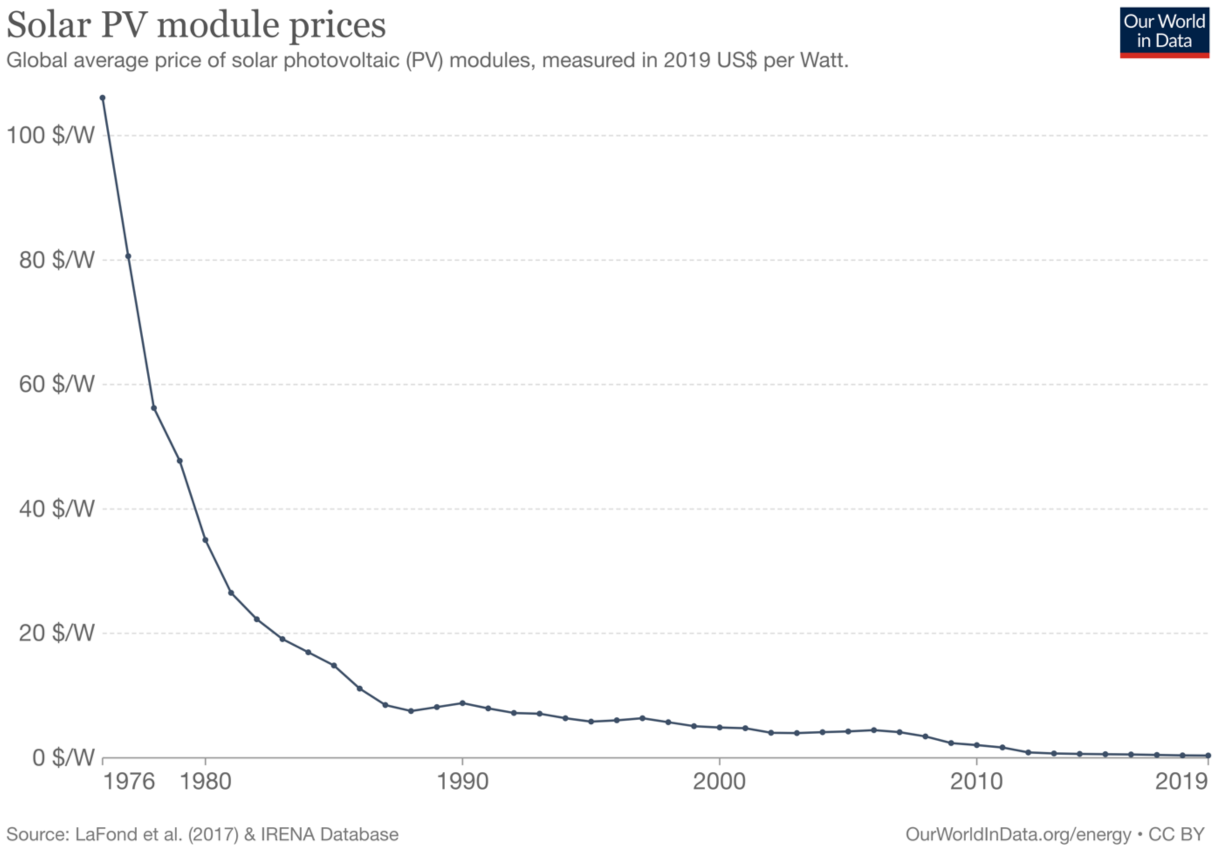


Figure 6: Evolution of PV panels prices throughout the years in the world [11]

This decrease in price, alongside government incentives and simplicity of installation, have made solar energy widely popular.

Merit-order

In short, merit-order describes a sequence of energy dispatch in which electricity generation power plants are ranked according to their marginal cost of electricity production. The lower the marginal cost, the cheaper it is to produce a single megawatt hour under recent conditions. The merit-order is, therefore, independent of the fixed costs of a power generation technology. It is used as a way to deliver power aiming at economically optimising the electricity supply [12].

As renewable sources have (near) zero marginal cost of energy they are ranked first in the merit-order (see Figure 7).

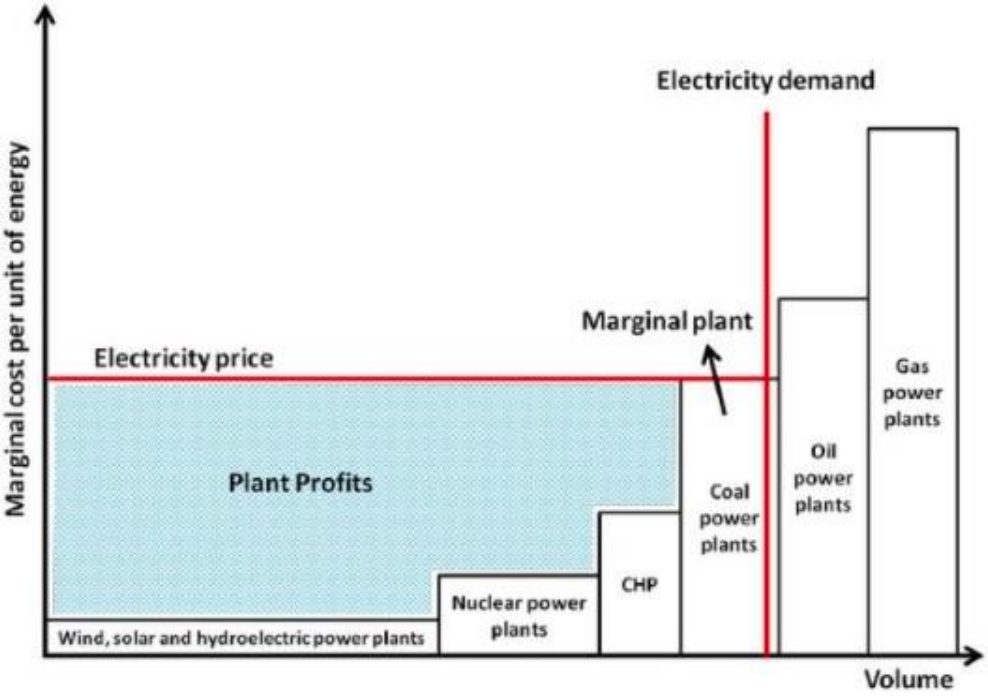


Figure 7: Merit order dispatch in electricity market [13]

There are some details (such as not being able to turn off a combined heat and power plant (CHP) because it depends on external factors and that some fossil fuel power plants have to run at a minimum because it is more expensive to turn them off and back on – case in which electricity prices could become negative), however, in general, the merit order favours the deployment of renewable sources of energy due to the (near) zero marginal costs.

1.2 Electrification

The use of electricity is likely to rise in the next few years in the EU. Traditional vehicles powered by internal combustion engines (ICE) will be replaced by sustainable alternatives, like electric vehicles. The heating, traditionally provided through gas in the Netherlands, will more and more be substituted by heat pumps, powered by electricity. The deployment of EVs and HPs will lead to a large increase in electricity demand.

Transportation accounts for one quarter of GHG's emissions in the EU [14]. Data from the EEA [15] show that emissions from passenger cars in Europe had their third consecutive yearly increase in 2019. However, the Netherlands is a relative global leader in EV deployment and EV charging infrastructure, with almost 200 hundred thousand registered EVs in 2019 [3], [16]. There are two main kinds of passenger EVs: fully electric vehicle (FEV) and plug-in hybrid electric vehicles (PHEV). The first one has the electric motor as a sole source of power and the second can run either on gas or electricity. On January 1st of 2020, the number of registered FEVs surpassed the number of PHEVs for the first time, as can be seen in Figure 8.

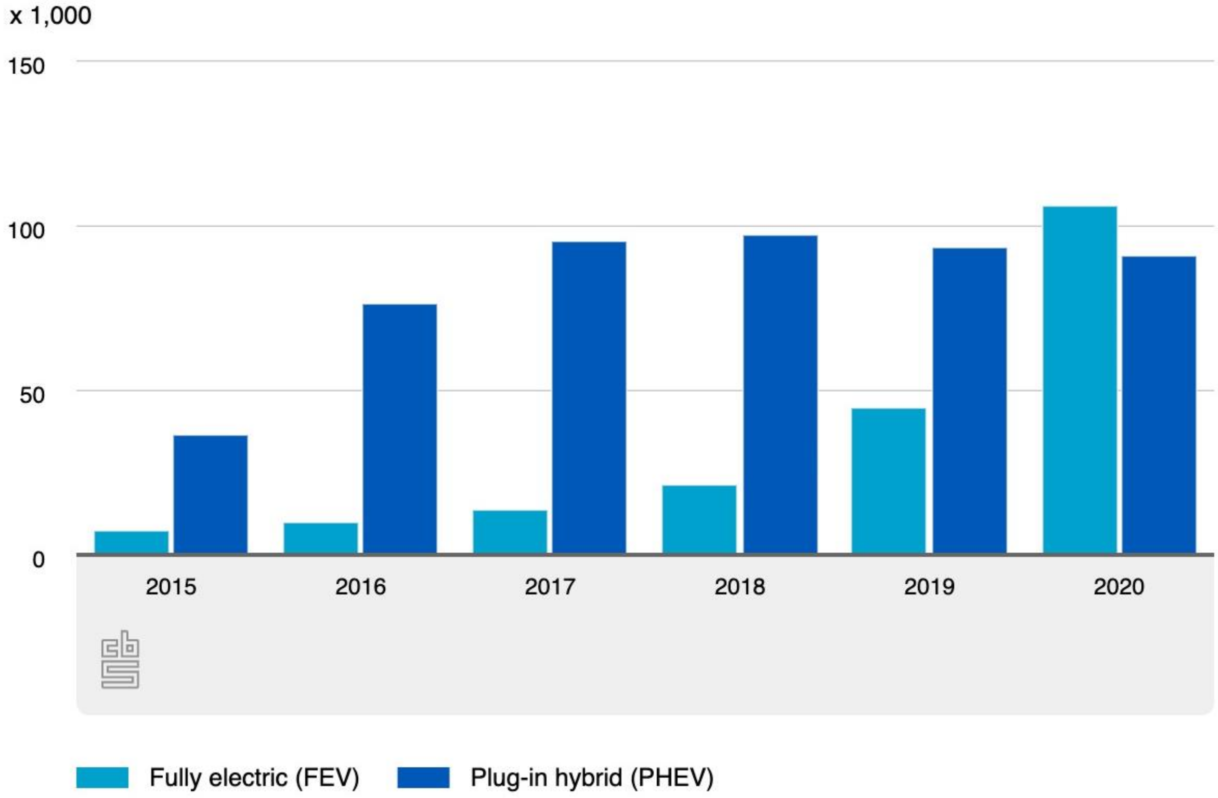


Figure 8: Number of registered FEVs and PHEVs [16]

The Dutch government announced in 2018 that it will drastically reduce (or terminate) the extractions from the natural gas field in Groningen no later than October 2022 [17]. Hence, Dutch households and buildings, traditionally connected to the NG infrastructure will have to change, as the government attempts to find new alternatives to heating spaces. Furthermore, the Dutch climate agreement states that one million buildings and seven million households will have to be disconnected from the NG pipeline by 2050 [18]. This is one more incentive for the deployment of heat pumps (HPs) [19].

1.3 Power system structure

The electric grid is considered by the US National Academy of Engineering the greatest engineering achievement of the 20th century. The electric grid is a network that enables the connection between generators and consumers through transmission and distribution networks [9].

The first central electricity generation facility was built in New York by Thomas Edson in the early 1880s. The station fed 400 light bulbs using a 110V Direct Current (DC) network. However, DC is not easily convertible to higher or lower voltages, thus the area that could be served by this network was limited. In 1886, Nikola Tesla invented the Alternating Current (AC), which led to the development of the first AC distribution system by George Westinghouse. The existence of DC and AC types of currents led to a battle known as the “War of the Currents”, that eventually ended with the victory of the AC current. This victory was due to the fact that technology from that time did not enable the transport of DC through long distances. Transformers were the technology available to transform voltage levels. Hence, historically AC was the only way to transport electricity with acceptable losses. Nowadays, our electricity is still predominantly powered by AC and its vast infrastructure. Some appliances, however, run on DC. Furthermore, as DC is more stable, there are companies finding manners in which to transport energy through high voltage direct current (HVDC) [20], [21].

AC is still cheaper to generate, though, and when transported through long distances has fewer losses than DC [22]. Furthermore, the entire infrastructure in place was designed to transport AC current, hence, the AC electricity system is still the one in use.

The (AC) power system is a large, complex, interconnected system. The structure of the Dutch high-voltage (HV) transmission system, shown in Figure 9, is owned by TenneT, that also owns over 10,000 kilometres of the 220 to 380kV grid in Germany [23]. In the Netherlands, the HV system ranges from 110kV to 380kV. The transmission system is used to transport large volumes of electricity over long distances and typically connects centralised generation to the largest industrial loads.

The transmission system furthermore (inter)connects the underlaying distribution system, which is operated on medium-voltage (1 to 50kV) and low-voltage (<1kV). This distribution system connects the majority of loads: medium-voltage (MV) networks typically supply medium-sized industrial and commercial loads, while low-voltage (LV) networks typically connect small-sized commercial and residential loads.

Figure 9: Map of the TenneT's high voltage physical grid in the Netherland – red: 380kV, green:220kV, blue: 150kV, black: 110kV [24]

1.3.1 Traditional power systems

The traditional, centralised power system is vertically integrated. Generation, transmission and distribution are all operated by one single entity [19]. Electricity flows in only one direction and is generated by one or more entities, whose only function is to generate electricity. In the vast majority of times, in this type of system, they are a monopoly. There is no interaction between utilities and consumers.

This “old way” meant that grid planning and improvement was mainly based on the demand for more electricity in a specific location.

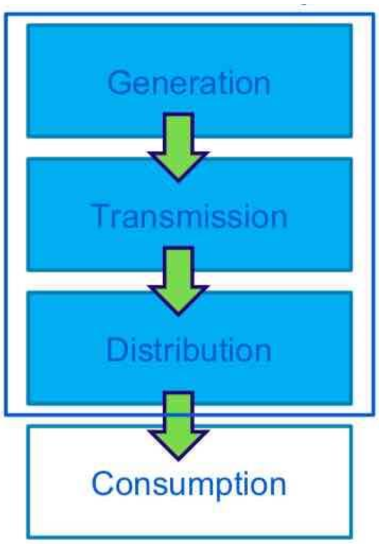


Figure 10: Traditional power system

As can be seen in Figure 10 it is a top-down system, mainly controlled by monopolies. The consumer has no choice of where it gets its electricity from.

1.3.2 Unbundled or liberalised power systems

The new system is composed by a mix of centralised and decentralised electricity generation. The biggest differences between the traditional and the new power systems are: the electricity flows in both directions (causing a bi-directional flow in a system that was designed for electricity to flow in only one direction); consumers are allowed to generate their own energy, becoming "prosumers"; transmission and distribution are typically unbundled from generation and supply, leaving the monopolists (typically systems operators) in a separate (regulated) entity; generation and supply are often liberalised, which means there is market competition, consumers get a choice; and there are many different sources of electricity generation. Electricity generation is privatised and the generators are owned by private investors [21].

The system must be balanced at all times. A balanced system means that the amount of power supplied to it is equal to the amount extracted from it. The frequency is an indicator through which it is possible to know whether there is an imbalance due to overproduction (underconsumption) or underproduction (overconsumption). If more power is supplied to the system than withdrawn from it, for example, the frequency of the system would rise [25]. Keeping this balance in the traditional system was simpler. When demand rose, more power was supplied through the power plants (and vice versa). Any mismatch between demand and supply threatens energy security and safety of the entire electric grid.

Electricity transmission (through the transmission system) is the responsibility of the TSO (Transmission System Operator). The TSO is an entity that acts independently from other electricity market players and transports (at a high voltage level) electricity to other market players (i.e., generating companies, traders, suppliers, distributors and directly connected customers) [26]. They also must guarantee the safe operation and proper maintenance of the system. TenneT TSO B.V. is the (only) TSO in the Netherlands.

The DSOs (Distribution System Operators) are responsible for connecting the TSO network through MV and LV connections. The three largest Dutch DSOs are Liander, Enexis and Stedin. The Netherlands has a single electricity market with taxes being imposed on a national basis. However, the systems are operated on different regional levels. Liander operates (among others) in Amsterdam, and in the provinces of Noord-Holland, Friesland, Gelderland; Stedin (among others) in Rotterdam, Utrecht, and most of Zuid-Holland and Utrecht provinces; and Enexis in five of the twelve Dutch provinces: Groningen, Drenthe, Overijssel, Noord-Brabant and Limburg [27].

An example of the new, unbundled system can be seen in Figure 11.

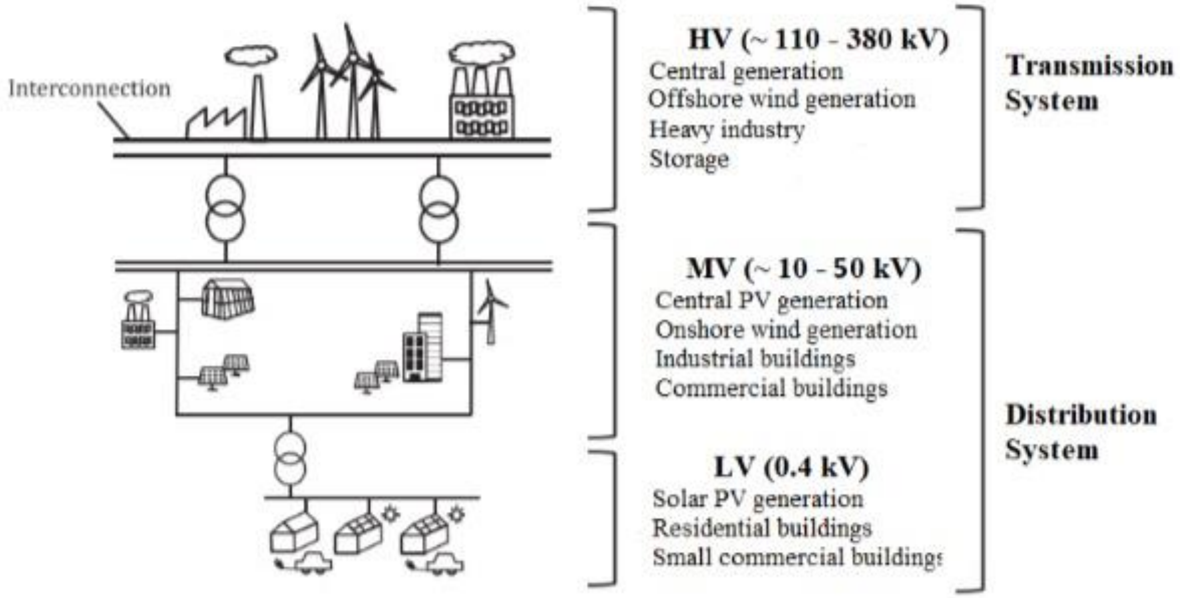


Figure 11: Unbundled electricity system [21]

In the Netherlands, the TSO and all the DSOs are government owned companies [21]. Collectively, TSOs and DSOs should: ensure market access and secure operations; facilitate the participation of all market players; define their needs clearly so that market parties can develop new and existing products; enable service providers to sell their products through a physical connection; whilst complying with the European GDPR, grid codes (both European and national), and national law [28]. Electricity generators, electricity suppliers, TSOs and DSOs are now legally separated entities [25].

1.4 Developments in the power system

Traditionally, the power system is organised in a centralised top-down manner and consists of matching energy demand on the supply side. This traditional approach can be referred to as demand-side driven

[29]. In this approach the power production, traditionally supplied by power plants fuelled by fossil fuels, is increased according to demand.

However, climate change and resource depletion have been threatening this traditional, demand-driven, manner to deliver electricity. With the addition of renewable sources this traditional way of generating energy has changed. The concept of decentralised power generation has become popular. Integrating these new sources into a power system that was designed for a centralised distribution, however, poses new challenges.

The ever-increasing numbers of renewable energy sources (e.g., solar photo-voltaic, wind turbines) that are being installed in the power system are replacing many of the fossil-fuel based power plants. However, these new sources have a volatile, weather-dependent, generation profile. This is making it harder to match supply to demand. Therefore, flexibility on the demand side becomes more and more relevant.

Furthermore, renewable energy sources are typically connected to the distribution system, which traditionally is not designed for such loads. In addition, increasing amounts of electric vehicles and heat pumps are connected to the power system, increasing the load on it. As a result, large parts of the power system are now congested.

It can be seen in the map in Figure 12 that almost the whole of the Netherlands already experiences or is on the verge of experiencing a large congestion in the electricity sector with regards to connecting new renewable energy sources. Further increases in electricity supply cannot be met through the existing infrastructure without taking additional measures. The traditional measure is reinforcing the network, but this is costly and time-consuming. An alternative solution, avoiding or postponing reinforcements, or even overcoming the time needed to make reinforcements, can be found in the concept of ‘flexibility’ (more in chapter 3).

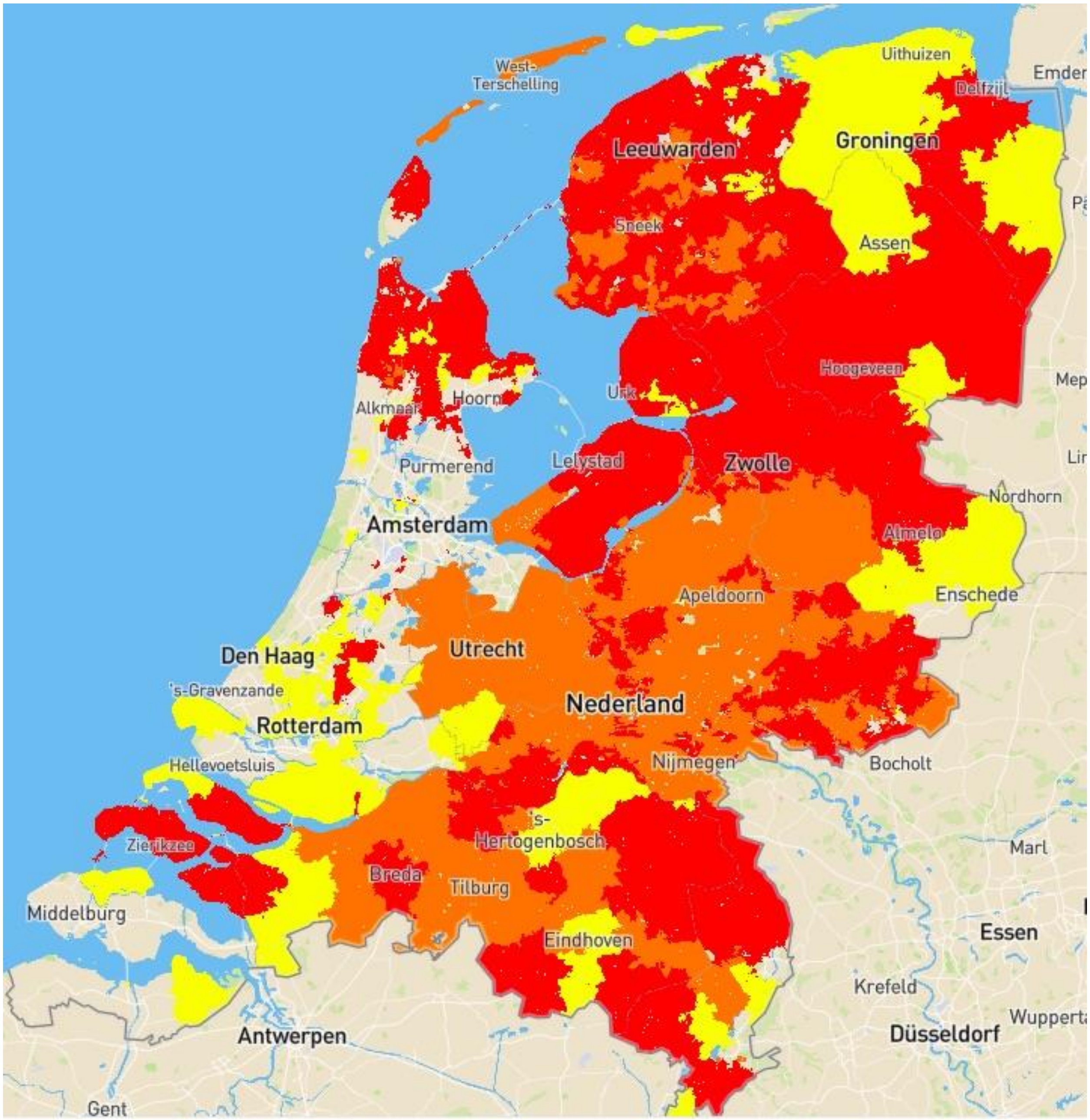


Figure 12: Congestion map of the Netherlands [30]

Transparent: no transport scarcity (yet)
Yellow: there is a threat of transport scarcity, an adjusted quotation regime applies
Orange: warning of structural congestion at the Authority for Consumers and Markets (the Dutch regulator)
Red: structural congestion, new requests for transport may not be attended.

2 Research methodology

In this chapter, the problem this thesis addresses is defined, followed by the main research question, that motivated this research. This research question is followed by a set of sub-questions that have to be answered first. Furthermore, the scope of the thesis is defined. Finally, a thesis outline is be presented.

2.1 Problem definition

The world faces an increase in population and in electricity use. The energy transition is leading to an increase in the use of (among others) EVs and HPs aiming to reduce the use of fossil fuels. If electricity continues to be generated and used in the traditional demand-driven manner, this continuous growth may prevent countries around the world to reach their greenhouse gases emissions reduction targets. The IPCC released a report presenting the harmful effects an increase of 2°C in relation to pre-industrial levels would have on the planet. A rise of 2°C would increase the risk of damage to ecosystems, species losses, extreme weather events, among others [5]. In order to keep the temperature within 2°C above pre-industrial levels GHG emissions must be reduced. To achieve this goal, the manner in which electricity is generated and utilised has to be modified.

The electricity sector around the world is experiencing a rise in renewable energy share. RES, however, is intermittent and, therefore, requires adjustments to the traditional energy use system. Additionally, it enables consumers to generate their own electricity, which causes a bi-directional flow of electricity. Furthermore, maturing of technology and sustainability incentives have led to increasing adoption of Heat Pumps (HP) and Electric Vehicles (EVs) and electrification of industrial processes (given that the area that is being studied is an industrial park). This trend leads to the electrification of these two major energy streams: heating and transport, traditionally powered by fossil fuels. The characteristics of RES, combined with increased peak loads due to the growth of electricity demand, calls for expensive reinforcements in the distribution network if no other alternatives are available. Thus, DSOs are pursuing different options in order to minimise the required investments in the distribution network infrastructure.

One of the options to match supply and demand when the supply cannot be controlled is to modify the demand profile. In order to shift from a demand-driven to a mix of supply-driven and demand-driven approach, knowledge about the user’s load profile is critical and necessary. Through the load profile the amount of available and potential flexibility can be assessed.

2.2 Research question

This thesis aims at modelling load profiles of business areas in the Netherlands, relate these profiles to local RES production, and employ these models to assess the potential for flexibility. Measurement data from a number of individual companies on the industrial park of Reiderland (a region in the north of the Netherlands) will be used in the analysis. Through these data a fictitious industrial park is created, to which local photovoltaic generation is added. The flexibility potential is assessed, and, subsequently, a sensitivity analysis is conducted. The final goal is to contribute to facilitate the energy transition through energy usage optimisation.

Optimisation in this context entails the use of resources minimising the investment needed to reinforce the grid whilst maintaining a suitable level of available energy to fulfil the business's main processes.

In order to achieve this goal, the following research question was formulated. The question will be answered through a theoretical case applied to a few companies in the business area of Reiderland:

In what way can a synthetic load profile, that can be applied to multiple types of businesses with minor changes, be used to assess the flexibility potential, given a certain amount of available RES?

In order to answer the main research question, a set of sub-questions were formulated. These sub-questions address different aspects of the main question and are stated below.

SQ1. Which flexibility sources are available?

SQ2. How can a general load profile be developed for companies in an industrial site?

SQ3. How does the PV generation change throughout the year in the Netherlands?

SQ4. To what extend can local supply and demand be matched?

SQ5. What kind of companies have the largest influence over that profile?

SQ6. What happens if more PV panels are added?

2.3 Scope

This section clarifies what items are within and out of the scope of this research.

Within scope
- Low and medium voltage distribution networks: this thesis will focus on models and methods applicable to the low and medium voltage network domains.
- Timeframe: the load consumption changes drastically depending on the season in the Netherlands. For the flexibility analysis a typical month in the Spring and a typical month in the Fall will be analysed.
- Energy transition scenario: energy transition scenarios present different paths to a more sustainable future. Assumptions related RES penetration will be made to analyse specific energy transition scenarios.
- Types of load profiles: 6 main kinds of companies will be defined. This work will study these 6 kinds of load profiles and aim at building one single model for each specific type of company.
- Electrical energy: this thesis will be developed within the Electrical Engineering department of the Eindhoven University of Technology, hence the only form of energy treated in detail will be electrical energy.
- PV as the only source of RES: solar PV is one of the most accessible RES, making it the likely option industries will choose, as this can be installed on their roofs.

Out of Scope
- High voltage networks: this work will focus on low and medium voltage networks, therefore, the high voltage network is not part of the scope of this study.

- Roof area available; although the amount of available roof area is an important factor restricting the maximum PV penetration, this thesis is not developing any algorithms to automatically obtain the maximum roof area per building.
- Monetary value of flexibility: electricity prices and costs of flexibility sources will not be taken into consideration in this thesis. Flexibility models will be built aiming at reducing peak loads and shifting electricity usage to a more suitable time of day, without explicitly taking into consideration electricity prices.
- Residential consumption/networks/areas: this thesis entails the study of load profiles of industrial parks, hence residential consumption is out of the scope of this work.
- Sources of RES, other than PV.

2.4 Methods

Thesis structure overview

In this research load profile synthetic models of different kinds of enterprises were developed through data of companies located in the industrial park of Reiderland, in the region of Groningen, in the north of the Netherlands. The data was used to fit 6 main categories: industry, supermarket, office buildings, restaurants, warehouses, and stores. Entrepreneurs in the Reiderland business park would like to make their energy supply more sustainable. The capacity of the power grid, however, is insufficient and the costs of expansion are too high to enable connections of the necessary number of solar panels. Most transformer stations in the area are owned by Enexis but some are owned by entrepreneurs. Since 2019, the council of Oldambt have been researching the feasibility of a smart energy network solution. They have narrowed it down to two possible solutions: Enexis took over a transformer station from one of the companies in the form of a trial, making it available to several companies. As a result of the trial the companies can use more sustainable locally generated energy. The second solution concerns the smart installation of solar panels. The entrepreneurs were presented with an optimum solution regarding number of panels, angles of installation, distance between panels, etc. [31] The DSO Enexis and the entrepreneurs (companies in the industrial park) are the main stakeholders in the project to investigate the possibilities to optimise the usage of the current energy network and potential resources.

Chapter 3 contains the answer to the first sub-question. Firstly, this chapter presents a brief description of how the concept of flexibility will be approached in this thesis. Then it moves on to presenting the answer to the first sub-question. Furthermore, it presents brief descriptions of the new roles in the energy system, a set of possible applications for flexibility, and a few flexibility mechanisms. In *Chapter 4* a brief description of how the model was created is displayed. Descriptions of the simulations performed are also presented. The chapter entails answers to SQ2 and SQ3. *Chapter 5* presents the results of the simulations performed and, with those, an answer to SQ4, SQ5 and SQ6. Finally, the answer to the main research question and the main conclusions and recommendations of this thesis are provided in *Chapter 6*.

3 Flexibility in the power system

The integration of renewables to the grid poses new challenges. Renewable energy is intrinsically intermittent, making it harder to match supply and demand. Additionally, the power system was never designed for large amounts of renewables on a MV or LV level (or even HV level), potentially overloading these parts of the power system. This is known as congestion. To prevent network congestion and optimise supply and demand of electricity in a system, flexibility can be used.

In order to effectively manage large-scale, variable renewable energy sources, flexibility sources need to be used and planned ahead of time. Flexibility has to be tackled in all sectors of the energy system, from power generation, transmission and distribution systems, storage and more flexible demand-side management [32]. A representation of all those sectors and how they are interconnected is shown in Figure 13.

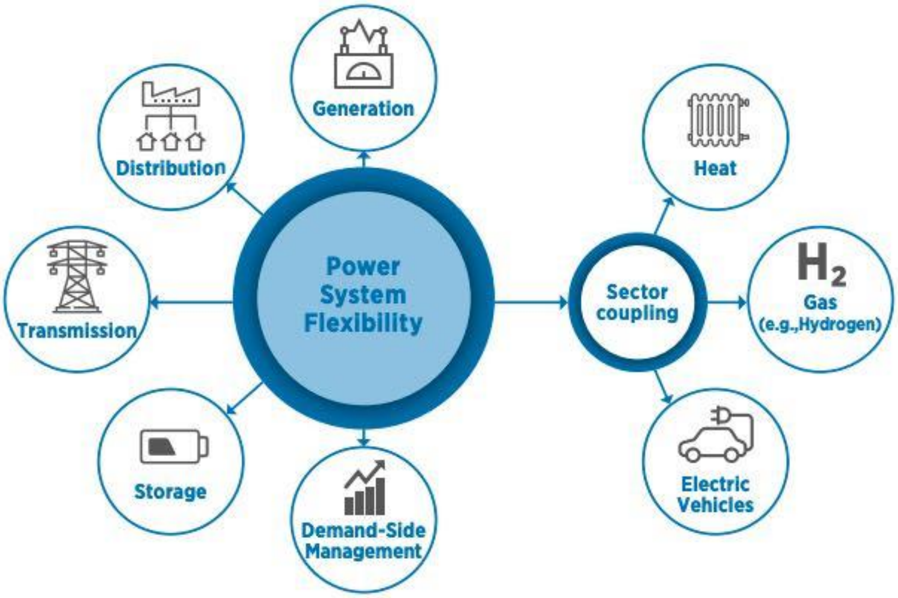


Figure 13: Power system flexibility enablers [32]

One of the interesting links in this figure facilitating flexibility in the power system is sector coupling. Sector coupling, in Figure 13, is the interconnection between the power sector and the broader energy sector, not usually powered by electricity. Examples are electric vehicles, and generation of heat and hydrogen through electricity [32].

Without the use of flexibility, the system with renewable energy sources is not able to cope with surpluses of generated energy. An example is shown in Figure 14. RES curtailment is a mitigation measure used when the surplus energy cannot be used locally used nor transmitted through the power grid. In those cases, the system operator decides to reduce the electricity output through, for example, limiting or disconnecting some of the PV system inverters. RES curtailment impacts negatively the economic attractiveness of solar and wind power (cheaper electricity, environmental impact, fuel savings, etc.) [32], and thus should be avoided.

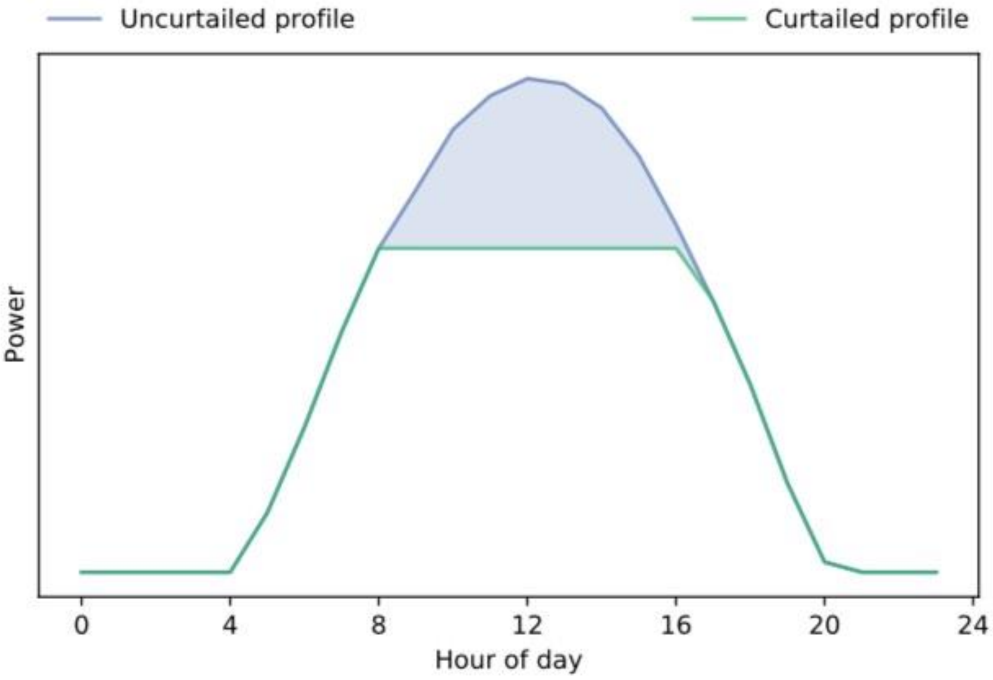


Figure 14: PV curtailment [19]

RES curtailment is an indicator that there are issues with the system flexibility. As it is, from an economic perspective, a "cheap" way for the system to cope with the surplus RES energy, market parties might choose to curtail the energy themselves (e.g., because of negative energy prices). PV curtailment can be prevented through flexibility.

There are other relevant roles in the liberalised system whose descriptions were not yet presented. These roles, as well as their respective description, will be presented in this chapter (section 3.1). A full overview of roles active in the power system can be found in [33]. This chapter will furthermore discuss the definition of flexibility (section 3.1) and a number of flexibility sources, applications, and mechanisms (sections 3.2, 3.3, and 3.4 respectively).

3.1 Definition of flexibility

There are various possible definitions of flexibility [34], depending on the application. For this thesis, however, congestion management is considered and therefore flexibility can be defined as the adjustment of power demanded or supplied at a given moment for a given period of time at a specific location in the network [35]. Through flexibility, electrical power demanded and supplied can be better aligned. Due to renewables' intermittent power generation, matching generated and demanded electricity is not a simple task. The ideal case would be for the surplus energy to be consumed locally, avoiding congestion in the electricity systems. Therefore, the aid of sources of flexibility is needed.

Aggregators cluster the available flexibility from all different sources and then sell clusters of flexibility to a pool of interested stakeholders. Flexibility can be sold, for example, to a DSO to avoid congestion [19].

Balance Responsible Parties (BRPs), whose responsibility is to keep the fed-in energy equal to the energy that exits within an imbalance settlement period and zone (and with that the system balance), are also an important role in the liberalised system. They provide energy programmes and predictions to TSOs. The programmes comprise data concerning the expected amount of fed-in and withdrawn energy per imbalance settlement period (ISP) or Programme Time Unit (PTU) – in the Netherlands a time-window of 15 minutes. One of the general goals of imbalance settlement is to guarantee the participation and support of the BRPs. Thus, give incentive to the market participants and maybe even decreasing the need for the TSOs to balance the system [36].

The **energy producer** is the entity that produces energy. Traditionally, energy producers were fossil-fuel plants. However, the share of renewable energy sources has been increasing rapidly. Through the control of the production it is possible for energy producers to provide supply-side flexibility [19].

The **energy supplier**, since the unbundling, can be considered a separate role. It procures electricity in the wholesale market or through bilateral agreements and supplies electric energy directly to consumers or other end users [19].

The **consumer**, in this new context, may possess assets that generate electricity (e.g., PV panels), becoming a prosumer [37]. The consumer is the end user of the electricity.

The DSO has an interest in flexibility because it can be used as an alternative to additional investments in grid infrastructure. Through flexibility network overload can be decreased by shifting the load to a period in which the demand is lower, offering the possibility of allocating electrical energy surpluses. The end user, in turn, has an interest in flexibility because the use of power can be shifted to periods in which electricity is less costly.

3.2 Flexibility sources

There are several appliances that can be used as sources of flexibility. One example is storage. Energy can be stored in many different ways, including:

- Pumped hydroelectric: electricity is used to pump water to a reservoir that can be used at another time to flow through a turbine to generate electricity [38].
- Compressed air: electricity is used to compress air in underground caverns. When electricity demand is high the air is liberated through an expansion turbine and thus generates electricity [38].
- Flywheels: flywheels is a way of storing kinetic energy. Electricity is used to increase the speed of a type of rotor. When the energy demand is high the spinning force of this rotor is used to turn on a generator [38].
- Batteries: electricity is stored in its original form. Depending on their size and specifications, batteries can store electricity for a long time [38].
- Thermal energy storage: electricity can be converted to thermal energy, which can be stored [38].

Heat Pumps (HPs) – that may be attached to thermal storage - and Electric Vehicles (EVs) – that may also work as a battery, supplying electricity to the grid - are examples of sources of flexibility. There are other appliances from which one can obtain flexibility, such as industrial processes, kitchen appliances and the ones already cited, but only those two will be further explained in this work (answer to SQ1). The choice was made due to their importance in the electrification of the energy system (two major energy streams that are traditionally powered by fossil fuels) and the facility to make them become sources of flexibility. Furthermore, if HPs and EVs are fully powered by the energy from renewable sources, carbon emissions will be drastically reduced.

A schematic diagram of the two primary kinds of electric vehicles that can be plugged into the electricity system are shown in Figure 15.

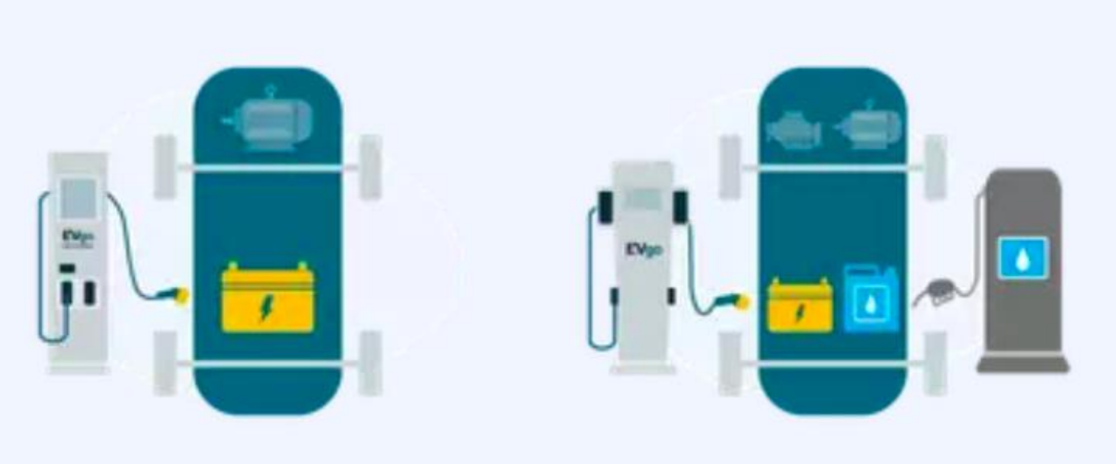


Figure 15: Diagram of a Fully Electric Vehicle (left) and of a Plug-in Hybrid Electric Vehicle (right) [39]

Hence, there are two primary types of EVs nowadays: Plug-in Hybrid Electric Vehicles (PHEV), and Fully Electric Vehicles (FEV). PHEVs generally have a battery linked to an electric motor. The battery is smaller than the one from a FEV. PHEV's batteries are charged from the grid. Hence, it is necessary to connect the vehicle to a charging point. Usually, when driving at slower speeds, the electric motor takes over until the battery runs out or the vehicle is accelerated over a defined threshold. The battery does not have to be empty for the engine to turn on. If the electric motor is excessively hot or cold, or features that draw more power are switched on (such as the air-conditioning) the engine turns on. The biggest advantage of PHEVs over FEVs is that in longer trips there is no need to worry about the battery running out, the ICE will turn on automatically when it does. With FEVs, however, there is the need of a minimum of charge in the battery for the vehicle to run. These produce zero carbon emissions locally [40]. In simple terms the time to charge an EV is given by:

$$Charging\ Time\ (h) = \frac{Battery\ Capacity\ (kWh)}{Charging\ Power\ (kW)}$$

According to the Netherlands Enterprise Agency [41] in 2021 the leading registered fully electric passenger car in the Netherlands was the Tesla Model 3. According to the EV database [42] the simplest Tesla Model 3 has a battery capacity of 57kWh. If a regular charging point of 22kW (top power capacity) is used, the most common in the Netherlands [41], [43], then the time to fully charge the battery will be approximately 2h40min. One of the advantages of an EV is that, depending on the model, charging point type, and regulations in place, it can also supply electricity to the grid (called vehicle to grid) [44][45].

Heat pumps are a key technology to decarbonise the heating (and cooling) demand of the building sector (if the electricity generation comes from a sustainable source). There are three kinds of HPs that can be clearly distinguished: Air Source Heat Pump (ASHP), Ground Source Heat Pump (GSHP) and hybrid Heat Pumps. All of them share the same principle: transferring thermal energy between places with different temperatures through the use of electricity. If the temperature outside is lower than inside the HP can provide space heating. If the temperature outside, on the other hand, is hotter than inside the HP can provide space cooling.

The number of HPs in operation in the Netherlands have been rapidly increasing in the last few years, as can be seen in Figure 16.

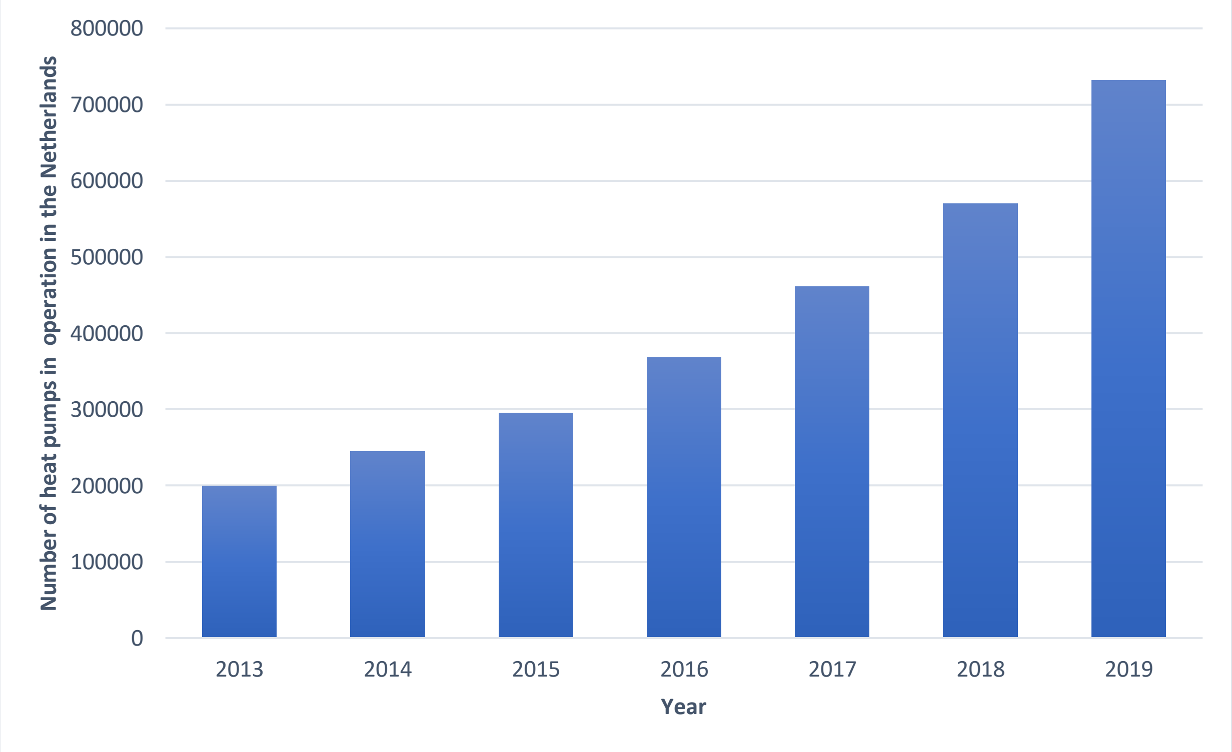


Figure 16: Annual amount of heat pumps in operation in the Netherlands from 2013 to 2019 [46]

The efficiency of a HP is expressed by its Coefficient of Performance (COP). The COP of a HP is a dimensionless coefficient that expresses the amount of thermal energy released over the electric energy consumed by the HP. This relation is shown by the equation below, in simple terms.

$$COP = \frac{Refrigerant\ effect}{Power\ input}$$

Hence, a higher COP is related to a more efficient HP. A COP of 5 means that for each kW of electrical power inputted in the HP 5kW of thermal power is released from the condenser or evaporator (depending on which setting the HP is set to work). Figure 17 shows a more detailed scheme of the operation of a HP for the cooling and heating seasons, respectively.

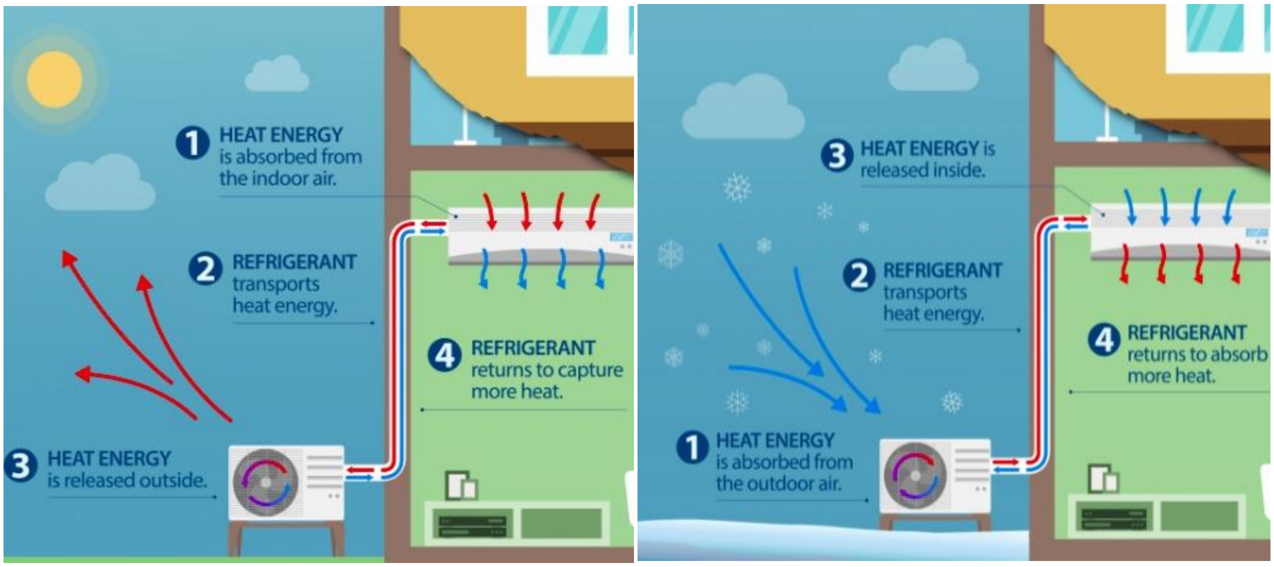


Figure 17: Heat pump set to cooling mode (left) and heating mode (right) [47]

HPs have the advantage of being highly efficient whether to cool or heat an enclosed space. They are also convenient (as their solely fed by electricity there is no need to worry about price fluctuations of NG or another fuel), safe (no risk of leakage of harmful gases), and, if their source of electricity is renewable, they contribute to a cleaner environment [47]. Furthermore, they can be coupled with thermal storage. This allows the time of use of the energy to be different from the time of energy production of PV panels [48]. Thermal energy storage offers flexibility to the energy system [49]. More information about the different methods and advantages of storing thermal energy can be found in [48] and [49]. More information about the different types of HPs can be found, for example, in [21] and [47].

3.3 Flexibility applications

Congestion management (DSO)

Congestion in the electric grid has become an immense issue, especially due to the energy transition, since the liberalisation of the European electricity markets. Congestion occurs if the power inferred by the geographical distribution of generation and load are too large to transmit through the existing capacity of the grid. During the past two decades, the geographical distance between generation and end-users has increased and thus the level of congestion (as it was shown in Figure 12). This is mainly due to three reasons:

- Thermal generation, with coal-fired often being the cheapest where cooling water is available (often close to the shore);
- Renewable energy generation, especially wind and solar, that are not always in the optimum location;
- Increasing integration of the European electricity market, increasing the numbers of imports and exports [50].

One of the possibilities to manage this congestion is to “shift” the use of energy. This can be done by redirecting the use of energy when it is less demanded by the system (e.g., by charging an EV when there is an energy surplus): flexibility.

Balancing (TSO)

According to the current European regulation, it is the TSO’s responsibility to maintain the balance in the grid. With the accretion of more RES in the energy mix this task becomes more difficult. Due to the intermittent nature of RES and the lack of an economically feasible mean of energy storage (particularly for long periods of time) imbalances between demand and supply are unavoidable (these imbalances always are present and the addition of RES to the energy system makes it even harder to mitigate them). In order to prevent grid instabilities these imbalances have to be corrected in real time by the TSO [51].

Energy arbitrage (market parties)

In economics and finance, the term “arbitrage” refers to the practice of taking advantage between a price difference between two or more markets, with the profit being the difference between the market prices. Arbitrage is practiced by energy market players through the purchase of electricity when the tariff is low and reselling it when the tariff is higher. By exploiting the difference in market prices the market parties make it economical to provide load shifting energy services [52][53].

Connection capacity optimisation

Flexibility can also be used by consumers or end-users to optimise their (contracted) connection capacity. End-users can use flexibility to consume the surplus electricity locally avoiding the need of a larger (more expensive) connection capacity. This way, due to the smaller peak in power generation, the end-user can have a smaller (cheaper) connection capacity [19].

Connection optimisation capacity in the HV network is for example used through the association of wind farms and battery energy storage. When the wind blows strongly sometimes the energy generated is too large for the electricity grid to handle. With the use of battery storage this energy, that otherwise would be lost, can be stored and used at another time when there is no wind [54].

There are also similar projects for large scale PV plants. An example is one being piloted by Enpuls, through which the theory and practice of battery use in combination with solar parks are being investigated. The pilot aims at making better use of electricity grid (with the introduction of new RES) and thus keeping the costs of the energy transition acceptable. The project involves a combination of peak shaving and a battery system. More about this pilot can be found in [55].

3.4 Flexibility mechanisms

Standard variable tariffs

There are other ways to encourage the use of electricity in off peak hours by consumers. Less costly tariffs are one example. Standard variable tariffs are also known as variant tariffs. It means that the price the customer pays per unit of electrical energy changes depending on the time of day they are using it. Figure

18, adapted from [56], shows a simplified way to illustrate the variable tariff scheme. According to IRENA, "*time-varying tariffs incentivise load adjustment, either manual or automated. This allows customers to save on energy expenses while benefitting the system*" [56]. Hence, by varying the tariffs (cost of electricity unit), demand-side flexibility can be unlocked.

Dynamic electricity pricing

An automated way of doing this is through the use of smart meters. Smart maters are devices that, depending on their class, can vary the functions available. Some smart meters can start and stop appliances according to what they are programmed to do. Those require a high level of digitalisation, automated communication, and control [56].

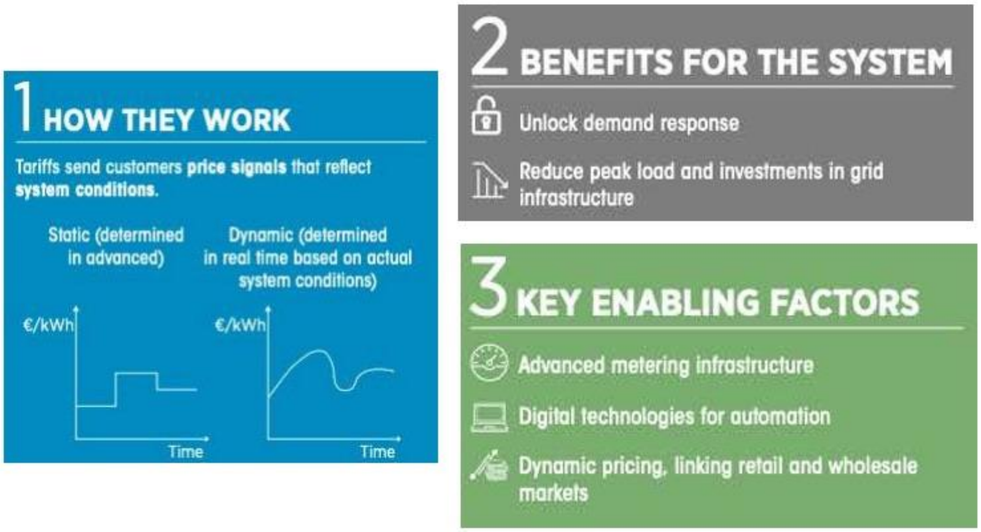


Figure 18: Simple description about the tariff scheme [56]

Through the creation of market signals, they motivate alterations in the electricity supply and demand. Hence, they could, for example, turn on a dishwasher when the price of electricity is lower. According to the director Internal Energy Market at the European Commission, in 2018, that could lead to a reduction of up to 400 euros per year in the electricity bill [57]. More details about how dynamic pricing of electricity works and the barriers to deploying it all around Europe can be found in [58]–[60].

Portfolio optimisation

The recent changes in the energy sector are increasing the importance of portfolio optimisation. Risk management through diversification of energy sources has become an important aspect for BRPs. According to TenneT, the Dutch TSO, BRPs are financially responsible for maintaining supply and demand within their own portfolio [61]. BRPs aim at avoiding costs related to imbalances that are charged in their portfolio. Flexibility can assist a BRPs in optimising trading portfolios [62] and reducing balancing costs that result from deviations between the scheduled and actual amount of electric energy provided/withdrawn from the grid [63]. Balancing services entail all services specified by the TSO to keep the grid frequency according to regulation [62].

There are many other mechanisms for which flexibility can be used. However, as this is not the main topic of this work, they will not be discussed. More information on energy flexibility can be found on the European Commission website [64] and is also provided in detail by USEF [62].

In the following chapters the answers to the research question will be presented through the use of flexibility.

4 Data and Modelling

According to Encyclo [65], a *bedrijvenpark* or industrial park is an area in or outside a city or village primarily intended for the establishment of commercial companies. This thesis uses data from the companies located in the industrial park of Reiderland, in the north of the Netherlands.

As during Summer months a lot of employees normally are not working and during Winter months there is very little sunlight, months in the Spring and in the Fall were selected for the analyses. These are denominated typical Summer month and typical Winter month, respectively. Within those months a typical weekday of Summer and a typical weekday of Winter were randomly selected. Based on discussion with experts the following assumptions regarding the selected days were made: it could not be a Monday, because it is the start of the week and some processes might still be going through a transient phase (e.g., pieces of equipment being turned on); nor could it be a Friday because on Fridays some companies allow their employees to leave early.

This chapter contains the data used in the simulations conducted. The simulations aimed at identifying different types of industry, generating a PV generation profile, and comparing energy production and consumption. The data will be presented in the next sections.

4.1 Data

Two main sets of data were used in the comparisons presented in this thesis: PV power generation and load profiles. The PV power generation profiles are obtained through the PVWatts Calculator tool [66]. The load profiles are actual measurement data from individual companies in the industrial park of Reiderland (Groningen, the Netherlands).

4.1.1 PV system data

PV systems are composed of one or more PV panels connected to an inverter. They are a clean and silent source of renewable energy. They can be installed from rooftops of residences to large scale PV plants. This is how PV systems basically work: the sunlight, composed by packages of energy denominated photons [67], falls onto a PV panel. Through a process called photovoltaic effect (see [68]), it induces a direct current. Each panel generates a relatively small amount of energy but can be linked to other panels, forming a solar array [67]. Although many devices work using direct current (e.g., laptop and phone chargers, EV charging, etc.) they were designed to be plugged into the grid, that supplies and demands AC [67]. Therefore, PV systems require a DC to AC inverter. A simplified diagram of a PV system with an (optional) energy storage system is shown in **Error! Reference source not found.**.

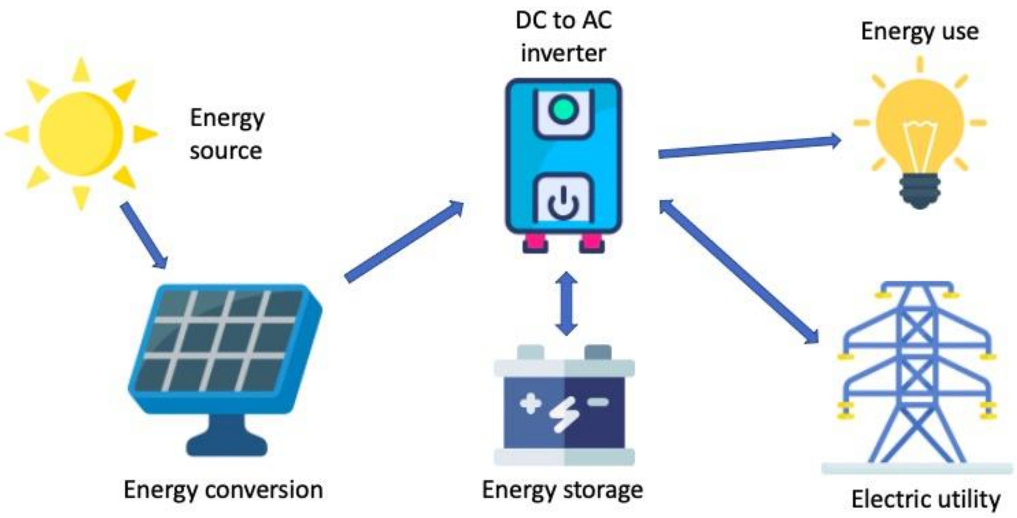


Figure 19: Simplified diagram of the main parts of a PV system with an energy storage system (optional)

All the PV system data was obtained through the tool PVWatts Calculator [66].

According to Energy Sage [69] nowadays, most solar panels have an efficiency between 15 and 20%. The default PV system size is 4kW and the area is calculated through the following equation [66]:

$$Size\ (kW) = Array\ Area\ (m^2) * \frac{1kW}{m^2} * Module\ Efficiency\ (\%)$$

Replacing the values in the equation above with an efficiency of 20% gives: Array Area (m^2) = 4kW / [(1kW/m^2) * 0.20] = 20m^2. This is just an example, if the efficiency is different from 20% the area needs to be adjusted. The same is true for the size (4kW) of the system.

The location for which the data was obtained was Groningen (53.3°N, 6.58°E). The other parameters used for the simulations can be found in Table 1.

Table 1: PV Solar System simulation inputs

Elevation (m)	4
Array tilt (degrees)	20
Array azimuth (degrees)	180
System losses (%)	14.08
Inverter efficiency (%)	96
DC to AC size ratio[1]	1.2

The simulation is estimated based on a typical-year weather file that represents a multi-year historical period [66]. For all purposes of this work this year will be 2018 because it is the year for which there are measurement data.

More information about how PV systems work and the specific characteristics and definitions of the parameters from Table 1 entail can be found in the documentation of PVWatts Calculator [66].

Figure 20 shows an overview of the energy generated through one set of the PV system.

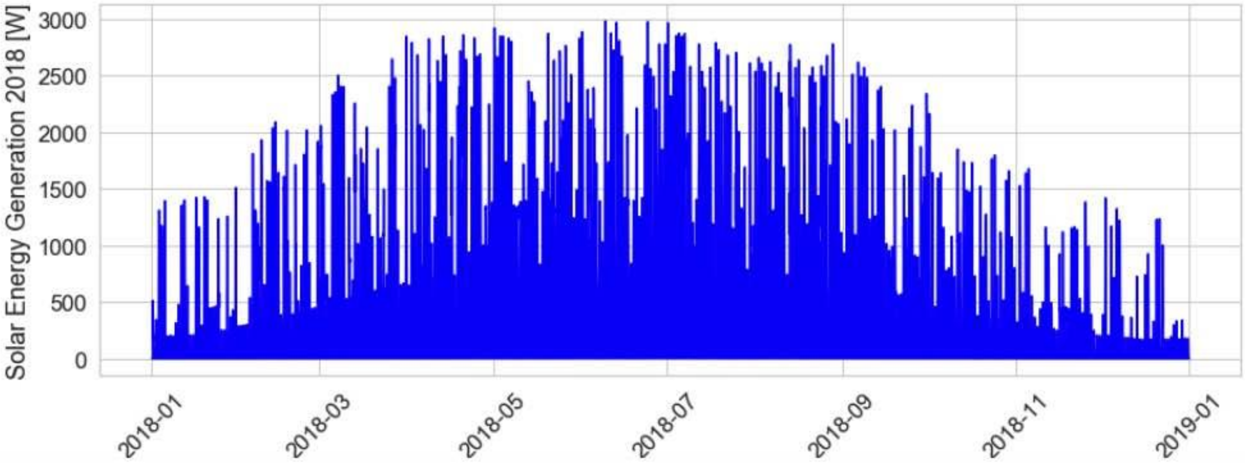


Figure 20: PV power production throughout a typical weather year

4.1.2 Load profiles

Load profiles of individual companies in industrial parks in the Netherlands can be further categorised based on the type of industry, such as shown by Das [70], or types of processes, such as in the methodology proposed by Janssen [25]. For this thesis, the companies were clustered based on types of

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[1] DC to AC size ratio means that not all the power generated in DC will be converted to AC. This happens because the nominal wattage of a PV system is determined under controlled laboratory settings. These settings are called Standard Test Conditions (STC), e.g., 25°C (normally the operating temperature of solar panels is higher), radiation of 1000W/m^2 (for real-life projects this depends on the location and time of year) etc. In real-life applications the PV system will operate below STC. Since a PV system operates below its nominal DC output, an AC inverter matching its capacity would be oversized. Hence, it is financially advantageous to have an inverter with a reduced AC output capacity. As a rule of thumb the DC to AC size ratio is 1.2, which means that for a 4kW DC PV system only a maximum of 3.3kW is converted to AC [79].

industry. The companies in the industrial park in Reiderland were divided into the following categories: industry, office, supermarket, restaurant, warehouse, and store. Furthermore, measurement data of a real-life industrial park (Reiderland, Groningen, the Netherlands) is used.

The available data is from the following number of companies for each of the types defined above:

- Industry: 10;
- Office: 10;
- Supermarket: 1;
- Warehouse: 1;
- Restaurant: 1;
- Store: 6.

Industry corresponds to all kinds of heavy industry, that manufacture different products. Office entails all kinds of office, private and administered by the government. The stores sell different kinds of products. Those are not all the companies present in the industrial park in Reiderland. Those are the companies whose energy consumption data were available. They were categorised by a person who was familiarised with the industrial park in Reiderland previous to the analyses.

For supermarket, warehouse, and restaurant there is only one example of each. Hence those will be the examples that will be used for those sectors. This is far from being ideal, however, for the purpose of this work - which focuses on determining the flexibility potential of industrial sites using load profiles and PV profiles - it will be sufficient. There is not enough data to draw any definitive conclusions from the other kinds of business either. However, it will be a good example as an initial study to test the result of the application of this methodology. Therefore, future research should focus on an improved methodology to develop the synthetised profiles, using a statistically relevant dataset.

4.2 Normalisation

Normalisation of the measured load profiles can be used to compare the different profiles of the various categories. By eliminating the absolute value, it becomes clearer whether the different profiles in a category (e.g., 10 office profiles) represent a similar behaviour. If this is the case, the profiles can be used to determine a representative profile for a synthesised industrial park, and the magnitude of the representative profile can be re-added to represent a certain amount – and size of a category.

The aim of normalisation is to make variables comparable to each other. Normalisation is important when there are two or more sets of data in different scales and the aim is to compare them. It is a way to bring the data all to the same scale so they can be compared. In the case of this thesis the companies were categorised by someone who had knowledge about what each of them was, before the data was normalised. With the normalised profiles, this initial categorisation could be validated.

For this thesis, normalisation was used to cluster load profiles from different types of industry. The types industry, office, and store, that had more than one example of each, were normalised and plotted together in a graph of each type.

The normalisation is made through the following equation:

$$NormValue = \frac{Value}{MaxValue}$$

where NormValue is the normalised value, Value is the value of energy consumption or PV generation at that given moment, and MaxValue is the maximum value that is consumed by the company or generated by the PV panels in a given period of time. Thus, the moment in which the normalised value is equal to one is the peak energy consumption of that company in a defined period of time. Figure 21 illustrates the steps followed for normalisation to cluster the different categories of companies in this thesis.

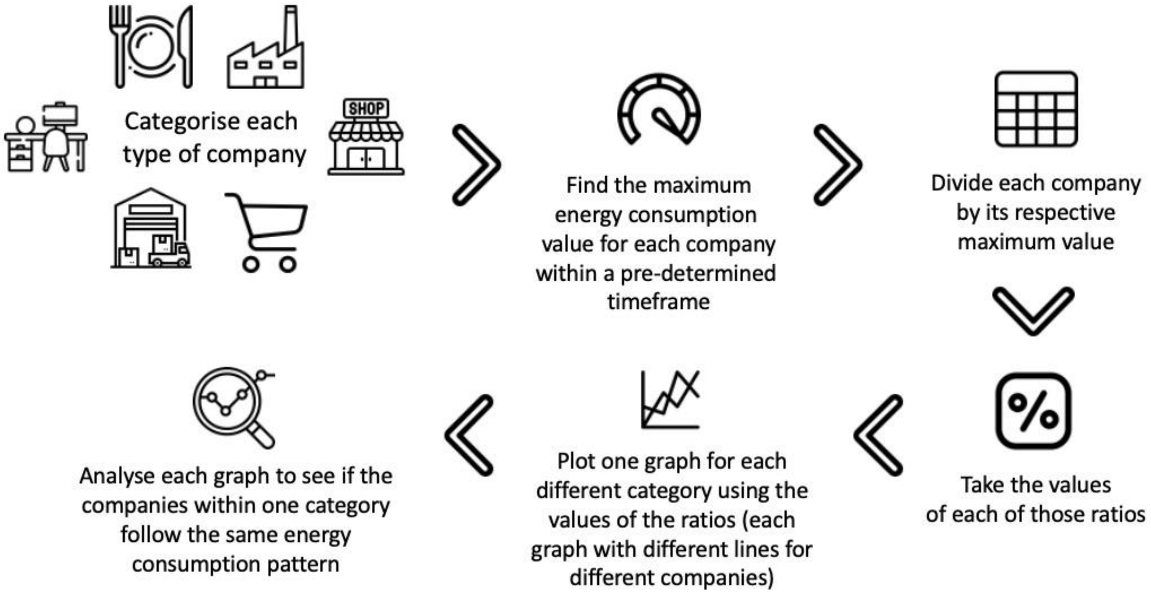

Figure 21: Steps followed to normalise and compare the data of the different categories of companies in the Reiderland industrial park

A synthetic profile is formed using the normalised load profiles of each of the categories. This synthetised load profile represents the behaviour of a company belonging to a category of industry, showing the variations in energy consumption of a company throughout the day. Based on the size of a company, and the amount of companies belonging to a category within a synthetised industrial area, the magnitude of the profile can be readded at a later stage.

4.2.1 Normalised load profiles

Figure 22 shows the normalised consumption of the whole industrial park of Reiderland (with data from the 29 companies analysed). In this case, the maximum value of the whole year was used for normalisation. It can be seen that the peak consumptions occur in February and between November and December. In those times of the year, most likely, most employees are working. The peak value corresponds to 866.7kW.

Figure 22: Normalised electricity consumption of the companies analysed from the industrial park of Reiderland

As stated in the previous section, absolute values are not always necessary. Especially when the goal is to cluster/identify specific types of companies.

Figure 23, based on a random weekday in May, leads to the assumption that companies from the category industry energy consumption follow no specific pattern and probably depend on the product they manufacture.

Despite being responsible for the vast majority of the electricity consumption in the Reiderland industrial park, there is not enough data to draw any conclusion with regards to a representative synthetic load profile. Without in-depth knowledge about the different processes each kind of product demands, it is impossible to relate different profiles. Therefore, it does not seem possible to have a single representative profile out of those. However, as not every industrial park in the Netherlands possesses this kind of business, for the goal of this thesis it is assumed the category industry is not part of the synthetic industrial park. Future research should investigate methods of including/synthesising industry, such that the results of this thesis can be applied on a broader set of industrial parks.

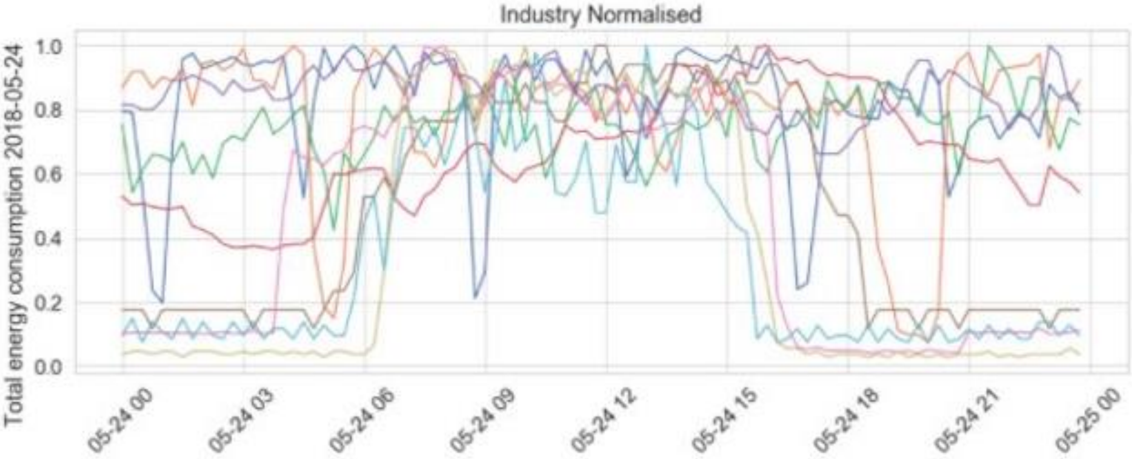

Figure 23: Normalised industry load profiles on a random weekday in May

In Figure 24 and Figure 25, on the other hand, it is possible to see clearer patterns for the office buildings' profiles.

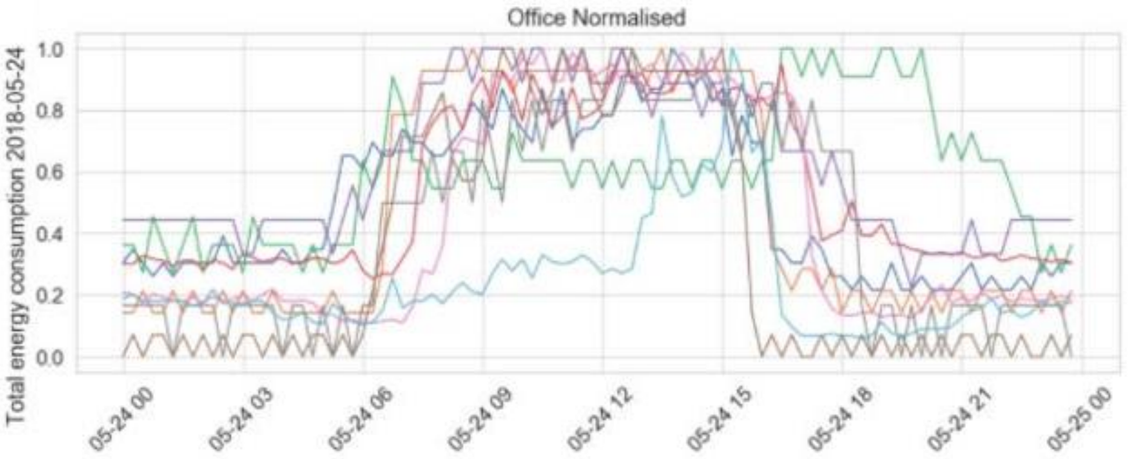

Figure 24: Normalised office load profiles on a random weekday in May

The only curves that differ considerably from the others (blue and green) in Figure 24 are both from companies that manage financial holdings [71].

Figure 25: Normalised store profiles on a random weekday in May

For stores (Figure 25) all the normalised profiles are very similar.

The same curve behaviour was observed on other weekdays. The plots above are presented as examples. That is the answer to SQ2: a way of generating a synthetic profile is by categorising the different types of companies, normalising their values, and plotting each different category in one single graph. For future research it is recommended to make a statistical comparison in addition to the visual one. As the dataset available is limited, the added value of implementing a statistical comparison was limited. Therefore, for this thesis it was chosen not to focus on this comparison.

4.2.2 Categorising different types of industry

Normalised profiles are useful to cluster different types of companies. In order to identify different types of industry it is necessary to know only how their energy consumption varies during a defined period of time. Measurement data from companies from the Reiderland business park was used. Six main types of business have been defined: industry (that manufacture different kinds of products), offices, supermarkets, warehouses, restaurants, and stores (that sell different products).

Restaurants, (wholesale) supermarkets are present in almost all (if not all) of the industrial parks in the Netherlands. Hence, even though each one of them only has one example, that example will be used to simulate a fictitious industrial park in the Netherlands. There is also only one example profile of a warehouse. This example will be used as the synthetic profile representing warehouses in the simulations of the fictitious industrial park.

The heavy industry type of industry does not seem to follow a defined pattern. There would have to be more data to draw any kind of conclusion. As this kind of industry is not present in every industrial park in the Netherlands, and there is not enough data available it is suggested as future research. With knowledge about the processes to manufacture each kind of product and statistics about how often a certain type of industry is present in an industrial park this can be done.

4.2.3 Normalised PV generation values

The amount of PV generation throughout the year, normalised by its maximum value, is shown in Figure 26. The data is from a weather station in Groningen, in the north of the Netherlands. This plot shows the ratio kW/kWp (kilowatt peak) throughout the year (providing an answer to SQ3). It is useful to have a better visualisation of how much solar energy is being generated, independently of the size of the system.

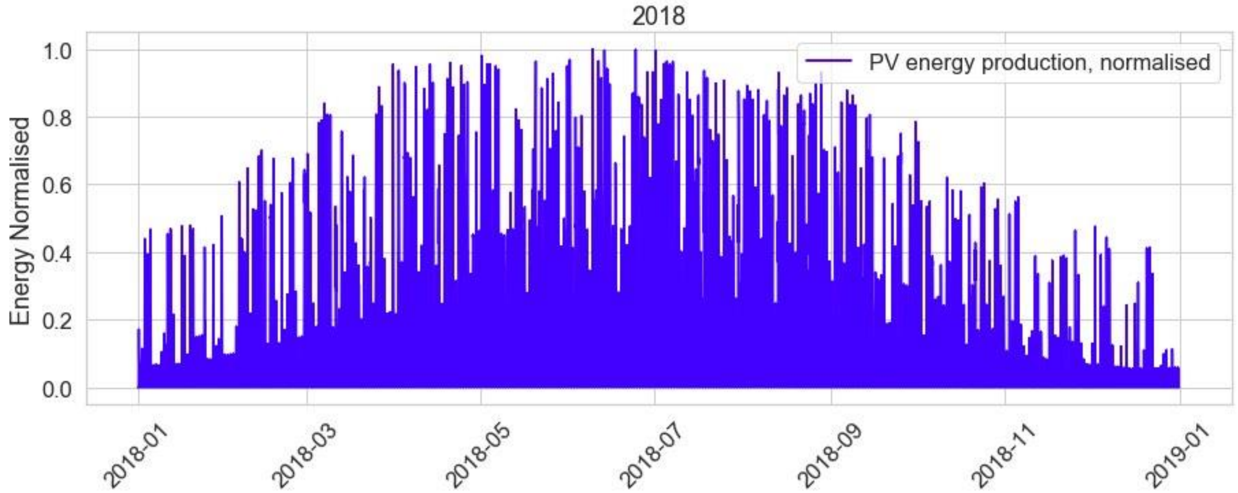

Figure 26: PV energy production throughout the year in the region of Groningen, in the north of the Netherlands [66]

As expected, the PV generation is at its lowest during the Winter months. The months of May and November were selected because they both have days of typical Summer and Winter, respectively.

4.3 Model

The companies that had more than one example were clustered and, as it can be seen in Figure 23, there is not enough data to develop a synthetic profile or further subdivide the industry sector. These companies, however, contribute immensely for the energy consumption.

All the data used in this section (4.3) are in actual measured absolute values.

Figure 27 shows how large this contribution is, in absolute numbers, of the industry sector from companies from which data was available. Despite not being taken into account in this work, the companies in the category industry are responsible for a large portion of the energy consumption in the industrial parks in which they are present. Figure 27 shows the difference of an industrial park with and without industry, generated from the available data.

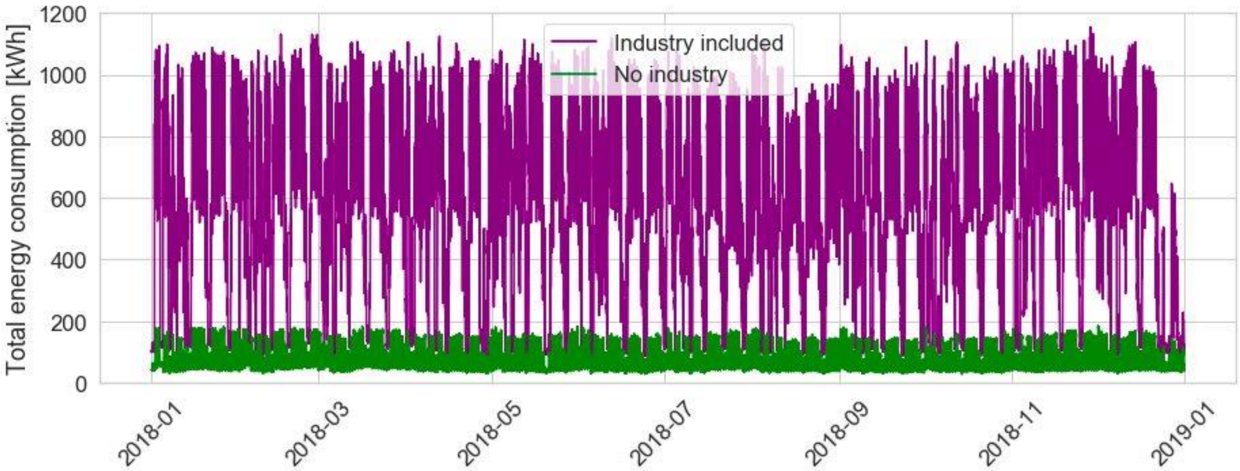

Figure 27: Total energy consumption of the original industrial park with the data available from the categories office, supermarket, warehouse, restaurant, and stores, with and without industry

Therefore, it is strongly recommended for future work to get more data to make it possible to understand and generate synthetic, wide-applicable, load profiles for the different types of industry.

For the other types of business, future research should analyse a larger dataset. Then, for example, a (complex) statistical analysis could be conducted. Outliers in the profiles would have to be defined, such as suggested by Wada [72], and other statistical procedures would have to be followed. This is strongly recommended for future work. For the purpose of this thesis (an initial study of the application of this methodology as a proof of concept), choosing one example from each type of business is considered to be sufficient.

To develop a fictitious industrial park the plots with absolute values (no longer normalised as in the previous sections) were generated. They are presented in Figure 28 and Figure 29. In order to compare the amount of PV energy generated and the load profile of the customers, the 15-minute load profile was resampled. The resampled dataset represents the average consumption per hour. A model of a fictitious industrial park is used in the simulations in chapter 0. This section contains explanations of how the data was selected for the simulations.

Many weekdays of May and November were analysed and the conclusion was that the office represented by the red line in Figure 28 and the store represented by the brown line in Figure 29 would be good representatives of the categories office and store, respectively. Their original magnitude will be used to compose the fictitious industrial park.

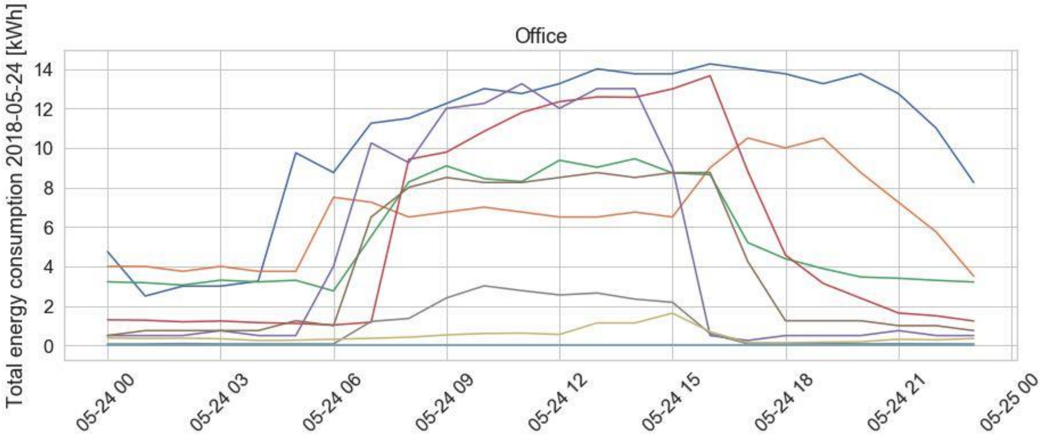

Figure 28: Plot containing all the business in the category office's load profiles

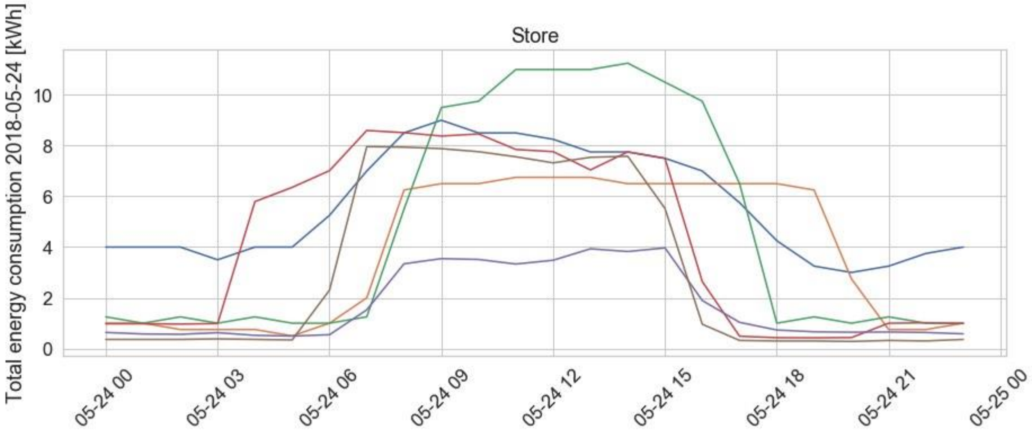

Figure 29: Plot containing all the business in the category store's load profiles

For the categories supermarket, restaurant, and warehouse there is only one example for each. Hence, they were chosen as the representative profile to compose the synthetic load profile for a fictitious industrial park.

In order to create a model with absolute values a specific company was chosen from each of the categories. For this model a number of companies from each category was selected to create a fictitious industrial park. Each type of company used the data selected to represent that category. For offices, for example, 10 times the magnitude of the red line is used (in Figure 28). For stores, 5 times the magnitude of the brown (in Figure 29).

Fictitious industrial park:

- Office: 10;
- Supermarket: 1;
- Warehouse: 2;
- Restaurant: 5;
- Store: 5.

In Figure 30 the load profile of these fictitious park can be seen.

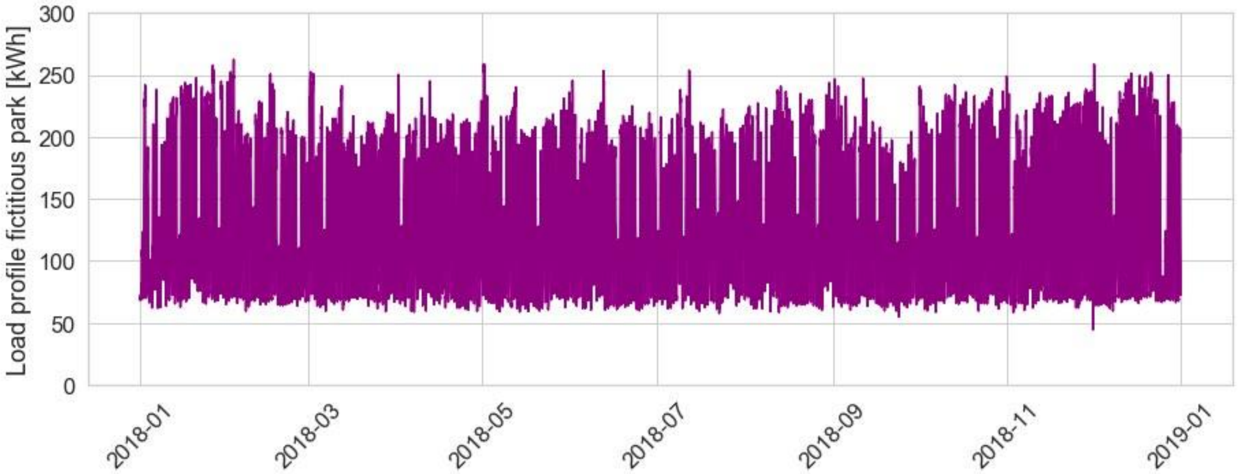

Figure 30: Load profile of the fictitious park described above

The data from the supermarket, the restaurant and the warehouse were not displayed to keep the confidentiality of those companies. This is due to the original magnitude of each of the load profiles that were chosen to represent their respective category being maintained. Hence, as each of those categories only has one example, if they were displayed separately, the company could be identified.

In the next chapter the results obtained from simulations with this fictitious industrial will be presented.

5 Results

Industrial parks are activity areas in which many types of industry are concentrated in the same space. They are often associated with a bad image due to what they may cause to the environment (pollution, damage to the biodiversity, etc.) [73]. The simulations performed and presented in this thesis aim at showing that an industrial park can be sustainable and environmentally friendly up to a certain point. How sustainable it can be depends on a series of factors, e.g., area available nearby, regulations in place, cooperation between the companies in the park, etc. Sharing infrastructure and premisses can be a big ally to make the industrial parks more “eco-friendly”.

5.1 Largest consumers

In order to answer SQ4 a series of graphs was plotted. Industry is, by far, the largest energy consumer in the Reiderland industrial park, represented by companies A to E in Table 2. The second largest electricity consumption category is from the category supermarket, represented by company F.

Table 2: Largest consumers in the Reiderland business park

Company	Peak Hourly Energy Consumption in 2018 (kWh)
A	305.25
B	266.75
C	215.50
D	205.25
E	77.50
F	33.25

As discussed in chapter 4, due to the volatile nature of industry load profiles (that probably depend on the kind of products they manufacture) more data would be needed to generate a generic, wide-applicable, load profile. To model industry load profiles in-depth knowledge of case-specific companies is required. Hence due to the lack of data and the fact that many industrial parks in the Netherlands do not possess this kind of business, industry is not included in the synthetic industrial park.

5.2 Simulations

Many different simulations were conducted using the fictitious industrial park load profile. Firstly, the amount of PV surplus was calculated. This is the amount of energy available for flexibility, after the whole fictitious industrial park energy needs were fulfilled. Afterwards the ratio of PV/Total Load profile was calculated to give an idea of how much of the fictitious park energy needs is being supplied by RES (i.e., solar energy). Finally, a sensitivity study was carried on, in order to see how modifying the PV penetration changes the results of this analysis (i.e., the energy available for flexibility in the fictitious park).

5.2.1 PV surplus for flexible applications

After the total energy need of the fictitious park is supplied in some times of some days there is still RES production/energy available. This surplus in production is the amount of energy that can be used for flexibility applications, such that the surplus is useful to the entrepreneurs and will not cause any possible congestion in the power system. In this thesis that surplus energy will be called the "PV surplus" (for flexible applications).

The amount of PV surplus can be calculated in two different ways:

- As an absolute number, that shows the total amount of energy available for flexibility;
- As a percentage, that represents the fraction of the energy system that is being supplied by the PV system.

This thesis shows examples of both ways to calculate the PV surplus energy. The advantage of calculating its absolute value is to have knowledge of the exact amount of energy that is available for flexible use.

The PV system shown in Figure 31 represent the total PV energy generated by a 400kW PV system and the surplus energy (what is left after the whole need current energetic need of the fictitious industrial is provided). Figure 32 and Figure 33 represent the selected months and days, respectively (as discussed in chapter 2).

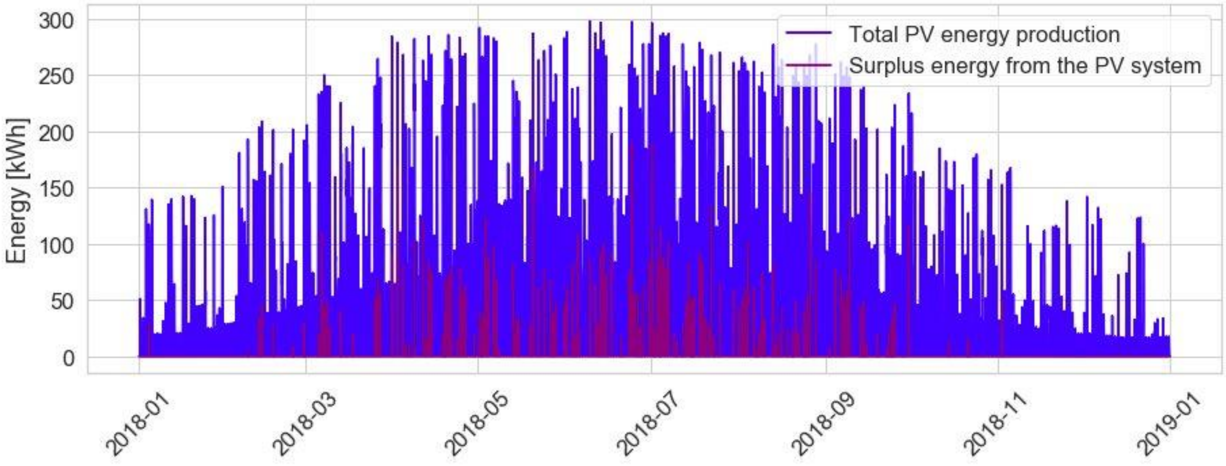

Figure 31: Total PV energy production (blue) and surplus (purple) throughout the year

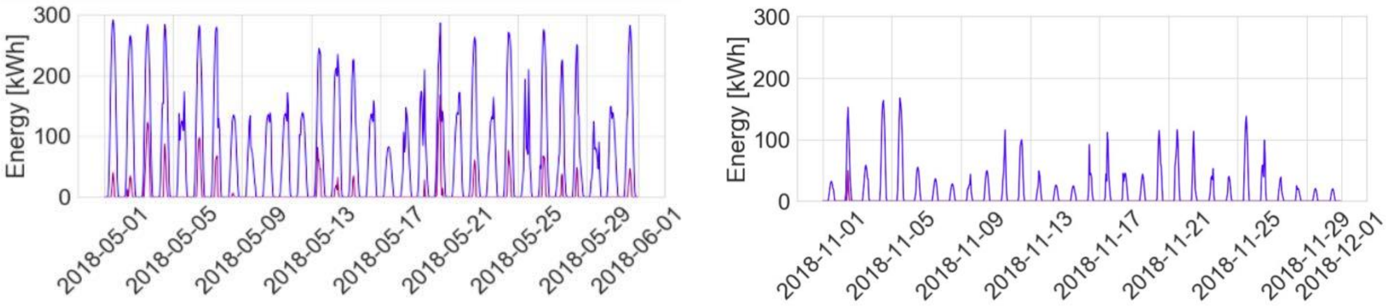

Figure 32: Total PV energy production (blue) and surplus (purple) in the months of May and November

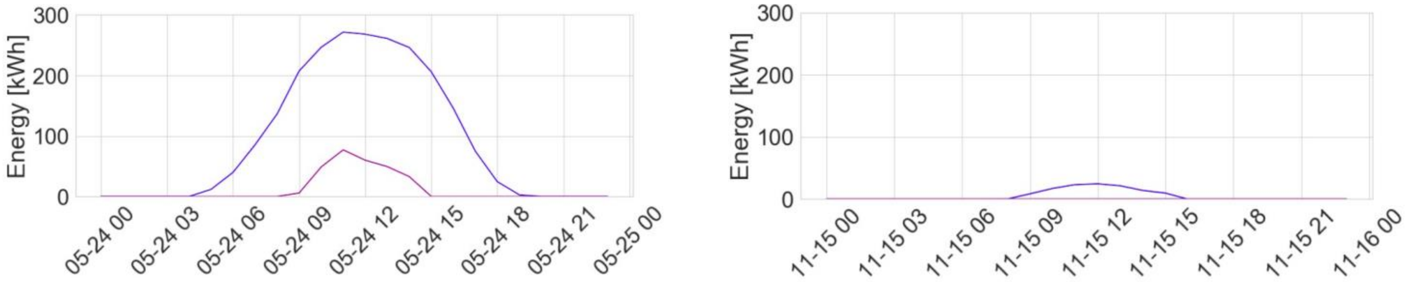

Figure 33: Total PV energy production (blue) and surplus (purple) on random weekdays in the months of May and November

The total energy surplus from the PV panels in a year for a system of this size is 25,151kWh. To make this number more tangible: this is enough to fully charge a Tesla 3 Model 441 times.

The mathematics for the use of HPs are, however, not that straight-forward. There are several models to assess HP flexibility (such as [74], and [75], that proposes a model coupled with automated demand response services applied on different HP systems working under real conditions). There was one study in the city of Eindhoven within the pilot Your Energy Moment [76], that also entailed the use of dynamic electricity pricing. However, there is no single, agreed-upon model and hence all illustrative comparisons will be made using only EVs.

5.2.2 PV/Load profiles ratio

As stated in the previous section, there is an alternative way to calculate PV surplus for flexible use. This method does not offer the actual value of the PV surplus energy, however, it offers the possibility of seeing the percentage of the energy system that is fed with PV energy in a given time of day. This enables a visualisation the share of energy provided by locally generated renewables.

The plot in Figure 34 shows that not only the PV system provides all the electricity needed in the fictitious industrial park, but it provides a surplus between 9h00 and 15h00, reaching a surplus production of 40%.

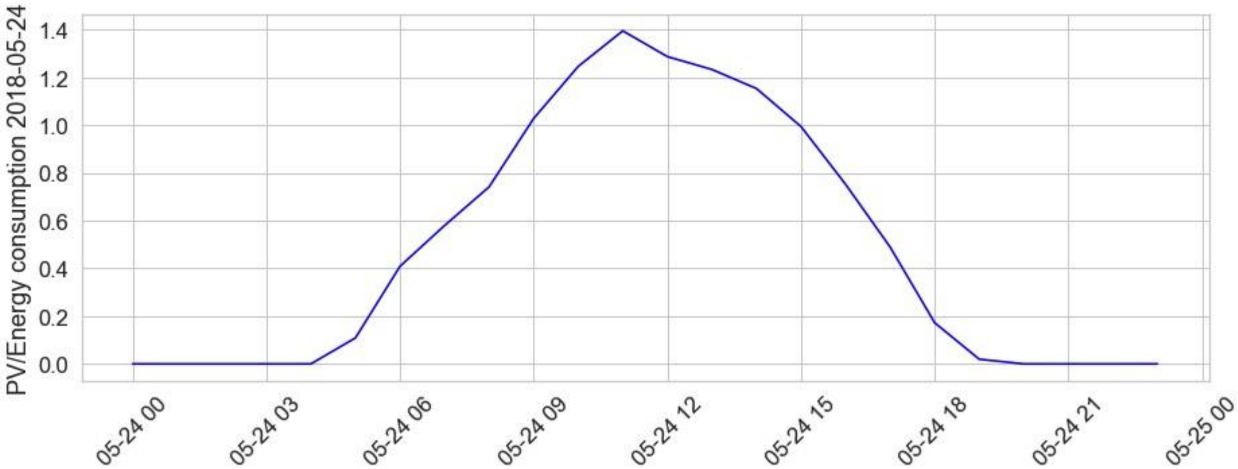

Figure 34: PV energy generated over energy consumption for the fictitious industrial park

Figure 35, on the other hand, shows that during typical Winter days the PV system is barely capable of providing any of the energy needed for the fictitious park. The plot in Figure 35 shows that the peak energy provided by the PV system is 12% of the energy consumed.

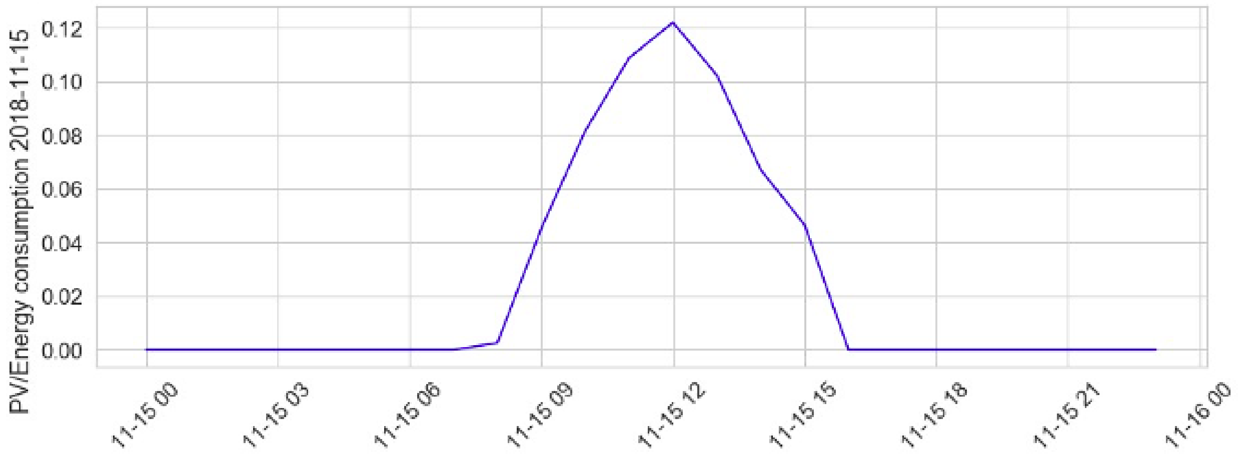

Figure 35: PV energy generated over energy consumption for the fictitious industrial park

Those plots provide an answer to SQ4 (to what extension supply and demand can be matched). For the baseline case (a 400kW PV system) it can vary from 12% (or even lower, on days with less sunlight) to even a surplus of 40% or higher (during sunlight hours).

Figure 36 shows how the ratio PV/energy consumption changes for the fictitious industrial park. The peak is in Summer, reaching a peak of over 2.5 (150% more than the required needs of the fictitious park), however, it seems to be well distributed throughout the year, except for the Winter months. In those the 400kW system provides very little electricity to the fictitious industrial park, only reaching 100% on a few occasions. Figure 36 reproduces the same kind of information from Figure 31, from a different perspective.

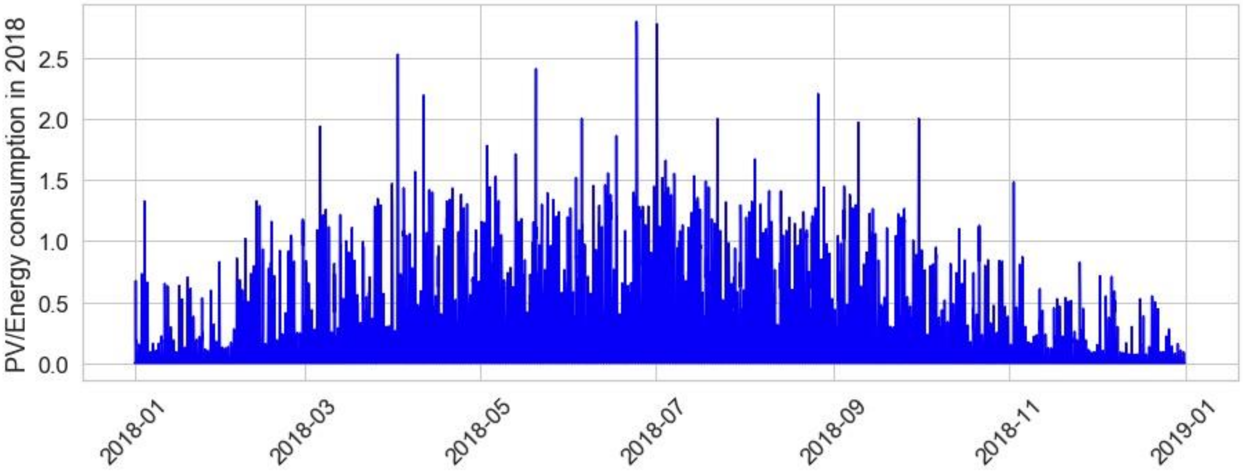

Figure 36: PV energy generated over energy consumption for the fictitious industrial park in 2018

5.2.3 Sensitivity analysis

The sensitivity analysis enables a visualisation of what would occur if to the PV surplus if the number of panels was to be increased or decreased.

If the PV system was 20% larger, it would generate 53,739kWh of surplus under the same conditions, enough to fully charge a Tesla Model 3 942 times, more than double the amount with 20% less the size. If it were 20% smaller it could only charge the Tesla Model 3 122 times.

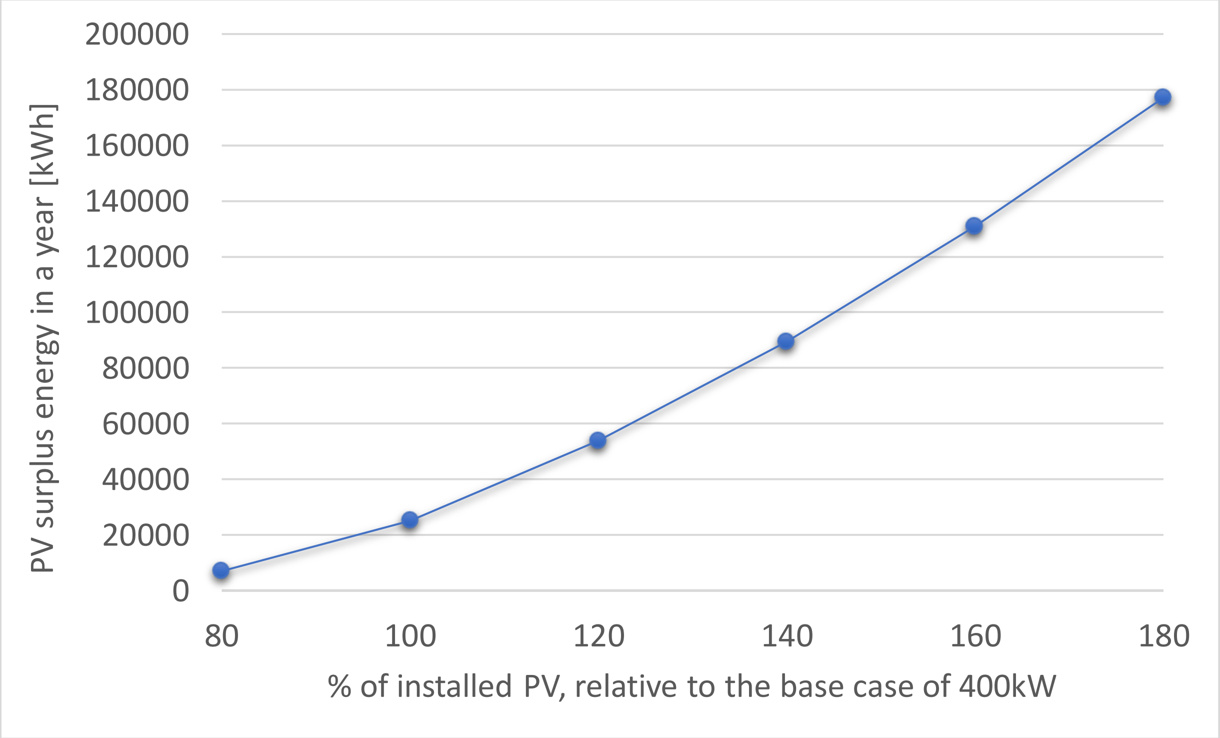

Figure 37: Amount of yearly PV surplus energy in relation to the % of the installed PV system

Figure 37 shows that the surplus energy grows exponentially as the number of PV systems is increased, reaching an amount that could charge a Tesla Model 3 3,107 times.

5.3 Discussion

The future of the electricity grid will probably entail more uncontrollable sources of RES than ever before. With the escalating deployment of EVs and the phasing out of the Groningen natural gas and the pursuit for new, low carbon emitting sources of energy, flexibility has to be used. In this thesis, the amount of PV energy that could be generated for a fictitious industrial park was calculated under the given conditions.

Roof area was outside of the scope of this thesis. Rouwhorst [21], in his thesis, takes into consideration the available roof area. Hence, as the area is not a restriction, the size of the PV system was not considered to be an issue. However, a complete analysis should take into consideration whether the area of 2,000m2 (according to the area of 20m2 calculated in section 4.1.1) is available on top of the roofs or in the vicinity. If PV panels with a higher efficiency were available a smaller area would be required to generate the same amount of PV power. Over recent years, the average panel conversion efficiency has increased from 15% to over 20% [77], that was the efficiency used to calculate the area of the PV system used in this thesis. There are PV panels available in the market with an efficiency of 22.8% [77]. Furthermore, a new kind of panel was able to reached 47% efficiency in the lab and 40% in the field [78]. Hence, it is a rapidly evolving technology, that only requires available area to be installed.

The initial idea of this thesis was to follow Janssen's novel framework [25], however, it was not possible. First of all, Janssen [25] did not have energy consumption data of all the processes executed by the companies in an industrial park. Secondly there was not enough information on what type of processes each of the types of industry utilises. In third place, there was no information about how many people worked at each company. Hence, Janssen's framework [25] could not be used.

The companies that have the largest influence on the electricity consumption in the industrial park are the ones classified as industry. This can be clearly seen on the graph of Figure 27. Hence the importance of obtaining more data from industry, its processes per type of industry, and the related electricity consumption. This is a first answer to SQ5 but there would need to be more data to build an actual synthetic profile of the companies classified as industry.

As explained in section 5.2.1, there are two different ways of calculating PV surplus energy, either by subtracting the absolute values from the total load profile of the park or by dividing the PV surplus by the load profile. It is possible to obtain different information from each of those calculation methods. From the first method it is possible to obtain the total yearly PV surplus energy and determine how much is available for flexibility use. Using the other method, it is possible to know how much of the load profile is being supplied by the PV system. The best method to use depends on what the information obtained will be used for.

It would have been ideal to have more data not only from the heavy industry sector but from the other types of companies as well. That way a more complete statistical study could have been performed. Using, for example, the method proposed by Wada [72] to define the outliers and posteriorly taking the average among the values left. In an even more advanced study, it would be ideal to find a relation between the number of employees and the energy consumption, for each type of industry, so the data could be properly escalated.

As it can be seen in Figure 37 the amount of PV surplus energy increases exponentially with the increase in number of panels until it reaches a more or less constant slope. This is probably because when more PV systems are added they are able to supply all the energy needs of the fictitious industrial park on some days, gradually. The constant slope means that every new system that is being added is surplus PV energy. This answers SQ6.

The application of flexibility to consume the PV surplus is not part of the scope of this thesis. An illustrative figure is given by the amount of electric charge cycles that can be done based on the amount of surplus. Future research should investigate how to exactly utilise the available surplus for flexibility. This is relevant, such that companies can shift to larger penetrations of RES, to fulfil in their base energy needs without causing (additional) congestion in the power system. When doing this analysis, additional sources of RES (such as wind) could also be included.

6 Conclusions and recommendations for future research

Conclusions and contributions

The analysis and simulations were conducted with measured data from the industrial park of Reiderland, in the north of the Netherlands. There were data from 33 companies in total. Not all data could be used for the analyses due to (mainly) lack of accuracy (some companies had a consumption of energy equal to zero). This limited the analysis and manipulations that could be conducted with the dataset, as the number of companies was limited.

Nevertheless, the main contribution of this study is that it was conducted with actual data and introduced a way of comparing data by bringing them to the same scale (through normalisation), after been subdivided into different categories. These clustered profiles could then be used to construct a synthetic profile for a hypothetical industrial park. With that, this thesis provides an initial step in developing a modular way of building representative syntactic profiles for any industrial park under investigation.

Specifically for the category of industrial loads, applying this method is not possible without additional research. Most of the heavy industry had very different behaviours, which leads to the conclusion that their energy consumption is highly dependent on product they manufacture. Hence, although industry is the biggest responsible for electricity consumption in an industrial park (see Figure 27) much more data would be needed to obtain one single, wide applicable, load profile. This extra information needs to include the (energy) behaviour of underlaying industrial processes.

For the other types of companies, it was possible to use the method described above. For the ones that had only one example of each (supermarkets, restaurants, and warehouses), those examples were used because the lack of data to compare them to. Furthermore, those types of business do not possess any kind of process that could drastically change their electricity consumption behaviour. Hence, a fictitious industrial park was created containing offices, stores, supermarkets, restaurants and warehouses, and its flexibility potential was assessed. With that, a proof of concept of the proposed method is provided.

Using the baseline PV system (a 400kW PV system) a Tesla Model 3 (most popular model of a FEV in the Netherlands) could be charged 441 times using the PV surplus energy. The sensitivity analysis furthermore suggests an exponential increase of available surplus energy for increasing levels of PV penetration. This provides an answer to the main research question: "*In what way can a synthetic load profile, that can be applied to multiple types of businesses with minor changes, be used to assess the flexibility potential, given a certain amount of available RES?*". Ideally, only the minimum adequate amount of PV surplus is fed back to the grid, to prevent worsening of the congestion issues in the Netherlands.

The peaks of surplus PV energy are probably mostly on weekends. In those cases, only the use of flexibility without storage might not be enough to avoid curtailment or feeding back energy to the grid.

Recommendations

The first recommendation for future work is to investigate methods with a broader industry dataset. This way the types of industry can be further subdivided into kinds of products they manufacture. This will enable the methods discussed in this thesis to be applied in a broader context, including industrial parks with a large set of industrial loads.

Alternatively, all the processes used to manufacture each kind of product could be identified. The research conducted by Janssen [25] gives the energy consumption of a few processes. More data about the electricity consumption from each process run by each kind of company (according to the product manufactured), could be studied and the sum of all the processes would be the total energy consumption for a given type of industry.

A deeper statistical study (ideally with many more companies' load profiles datasets) would also be a way of improving this work. Wada [72] suggests ways to determine outliers, which would be the first step for a deeper statistical study of the data. Subsequently, the average of the values left should be taken.

It is recommended to furthermore research the application of flexibility to consume the PV surplus. This thesis only provides an illustrative figure of electric charge cycles that can be done based on the amount of surplus. Future research should investigate how to exactly utilise the available surplus for flexibility. When doing this analysis, additional sources of RES (such as wind) could also be included, potentially achieving higher levels of self-consumed RES production, due to the diversification of the production.

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